Preliminary Design Study for an Electron Beam Driver Upgrade at the Holifield Radioactive Ion Beam Facility

A report prepared for the HRIBF Science Policy Committee by

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Section 1. Introduction and Overview

The Holifield Radioactive Ion Beam Facility (HRIBF) is a national user facility operated by Oak Ridge National Laboratory for the D.O.E. Office of Science. The primary mission of HRIBF is the study of low energy nuclear physics (nuclear astrophysics, nuclear structure and nuclear reactions) with radioactive ion beams [1]. HRIBF operation is based on two accelerators (see Figure 1), the Oak Ridge Isochronous Cyclotron (ORIC) and the 25 MV vertical Tandem accelerator. Radioactive beams are produced using the Isotope Separation On-Line (ISOL) method. A driver accelerator is used to generate the radioactive nuclear species in a production target and ion source assembly (referred to as a target/ion source, or TIS). At HRIBF, the k=100 ORIC cyclotron is used as the driver accelerator, and the Tandem serves as a post-accelerator. It provides beams of light ions: protons, and deuterons up to energies of ~50 MeV and currents of 10 to 20 μA, and helium ions of intensities up to a few μA with an energy limit of ~100 MeV. The radioactive beams are generated in the TIS assembly installed on a high voltage deck between the driver and the post-accelerator. The beam from the TIS is mass analyzed, converted to a negative beam in a Cs vapor cell (if necessary), accelerated from the deck through an isobar separator for high-resolution mass analysis and injected into the low-energy end of the Tandem accelerator. The accelerated radioactive ion beam is further analyzed at the exit of the Tandem accelerator and transferred to the various experimental facilities located throughout HRIBF. The combination of the ORIC and the 25 MV Tandem accelerator is capable of producing both proton-rich and neutron-rich radioactive ion beams. In particular, the 25 MV Tandem can accelerate all of the neutron-rich fission fragments from a uranium production target to energies above the Coulomb barrier for essentially all targets.

The HRIBF is now in the midst of an upgrade that will add a second ISOL production facility and consequently substantially improve both the efficiency and the effectiveness of the facility. We expect this upgrade to increase the number of hours of radioactive ion beam (RIB) that we can deliver to experiments by more than 50%. It is prudent to consider if there are further cost-effective additions to the HRIBF which we can make that can be justified within the current plan for RIB science in the U.S. Sound arguments can be made for the need to improve both the driver accelerator capability and the post-accelerator capability at HRIBF. This document considers in some detail a proposal to add a new driver accelerator to HRIBF that would add very significantly to the performance of the facility. This appears to be the most cost effective path that we can pursue at this time. Several options were examined for a driver upgrade. Replacement of ORIC with a modern commercial cyclotron (or linac) is an obvious option. All machines that were identified which would offer significantly improved RIB performance cost $20M or more. A second option is an electron beam driver that would be used to induce photofission in the production target. The electron driver has the disadvantage that it only improves performance for neutron-rich beams, but the level of performance improvement can be several orders of magnitude, and the cost of a high-power electron accelerator is likely to be less than $10M. The electron beam driver concept was originally proposed as a low cost addition to a Tandem facility [2] and has been adapted at other facilities [3]. It was also seriously considered as an option for the SPIRAL II upgrade at GANIL [4] in France. GANIL chose to use the larger and more costly (~$170M total cost) option of a high-current superconducting linac to provide 5000 μA of ~40 MeV deuterons to generate a secondary neutron beam by breakup on a carbon converter target and subsequently provide neutron-rich species from neutron-induced fission. This combination <u>may</u> be capable of the production of almost an order of magnitude higher fission yield than can be obtained with the electron-beam driver and has the added flexibility of heavy ions as a driver beams.

Both cost and timing are critical issues for an additional upgrade to HRIBF. To have a significant chance of funding, an upgrade should be modestly priced, fit within the limited real estate surrounding the existing facility and not require a large increase in technical and operations staff. A new driver accelerator should also be either commercially available or be capable of development by the vendor with only modest extensions of existing technology, and should be available from within approximately two years of receipt-of-order as a turnkey accelerator. Otherwise an upgraded HRIBF would come online too late to justify the cost and effort. The following list summarizes requirements for a potentially successful upgrade.

1) Must fit on the limited real estate available either near or within the existing facility
2) Must provide a minimum of 10^{13} fissions/second in the production target without assuming major technical developments in targetry.
3) Must be cost effective (an upper limit in the \$20M to \$30M range; the accelerator cost must therefore be ~\$10M or less)
4) Must require only a limited addition of staff for both operations and maintenance.
5) Should be completed in time to have significant impact on science before the next-generation facility is available.

Based on these considerations, an electron-diver upgrade has been selected. The technical basis of the facility is explored in the remainder of this document. In Section 2 physical effects associated with fission rates and energy deposition in the target are explored in some detail. A very conservative target geometry and composition consistent with those now in use at existing facilities is adopted, and the question of whether the goal of 10^{13} fissions/s can be achieved is explored, and answered affirmatively, even if the power density deposited in the target is limited to what has already been demonstrated at HRIBF. More exotic target geometries can lead to substantially higher yields. In subsequent sections of this document, a variety of technical, design and safety issues relevant to an electron-driver upgrade at HRIBF are discussed and a baseline upgrade design is proposed.

The electron-driver option operating at the nominal (and conservative) 10^{13} f/s rate provides very substantial gains in the intensity of neutron-rich beams at HRIBF, ranging up to a factor of $\sim 10^4$ for the most neutron-rich species (see figures 2, 3, 4 and 5 for expected performance.). This has a dramatic impact on the range intensity of beams that can be provided to experiments. Neutron-rich beams which we will be able to produce form an important part of the science program laid out for RIBs. However this upgrade does not address the production of proton rich species at all. We find that to have a comparable impact on proton-rich RIBs would require a much larger investment. Nevertheless we plan to make significant improvements to our proton-rich beam capability by taking advantage of the driver redundancy offered by the availability to improve the performance of ORIC by a series of modest-cost upgrades, including replacement of the internal ion source by an external axial injection system. This program will be presented orally.

An obvious omission in the present document is a discussion of the scientific justification for the facility upgrade. The relevant material has been collected and presented many times over the past decade as a pert of the justification for RIA. We have chosen not to reproduce this material again here. The subset of the broad program in RIB-related science which can be addressed at an upgraded HRIBF will be covered in oral presentations and discussion.

You should note that references and figures are numbered separately in each section of this document.

References

1. Proceeding of the workshop on the Production and Use of Intense Radioactive Beams at the Isospin Laboratory, Joint Institute for Heavy Ion Research, Oak Ridge Tennessee, Oct. 1992.
2. W.T. Diamond, A Radioactive Ion Beam Facility Using Photofission, Nucl. Inst. And Meth. A432, p. 471 (1999).
3. The ALTO Project at IPN ORSAY, Authors: **F. Ibrahim** **(IPNO)**
   International School-Seminar on Heavy-Ion Physics 7 (2002)
   Journal-ref: Yadernaya Fizika 66 (2003) 1445-1452.
4. SPIRAL II Project (Electron Option), Preliminary Design Study, GANIL/SP12/007-A.

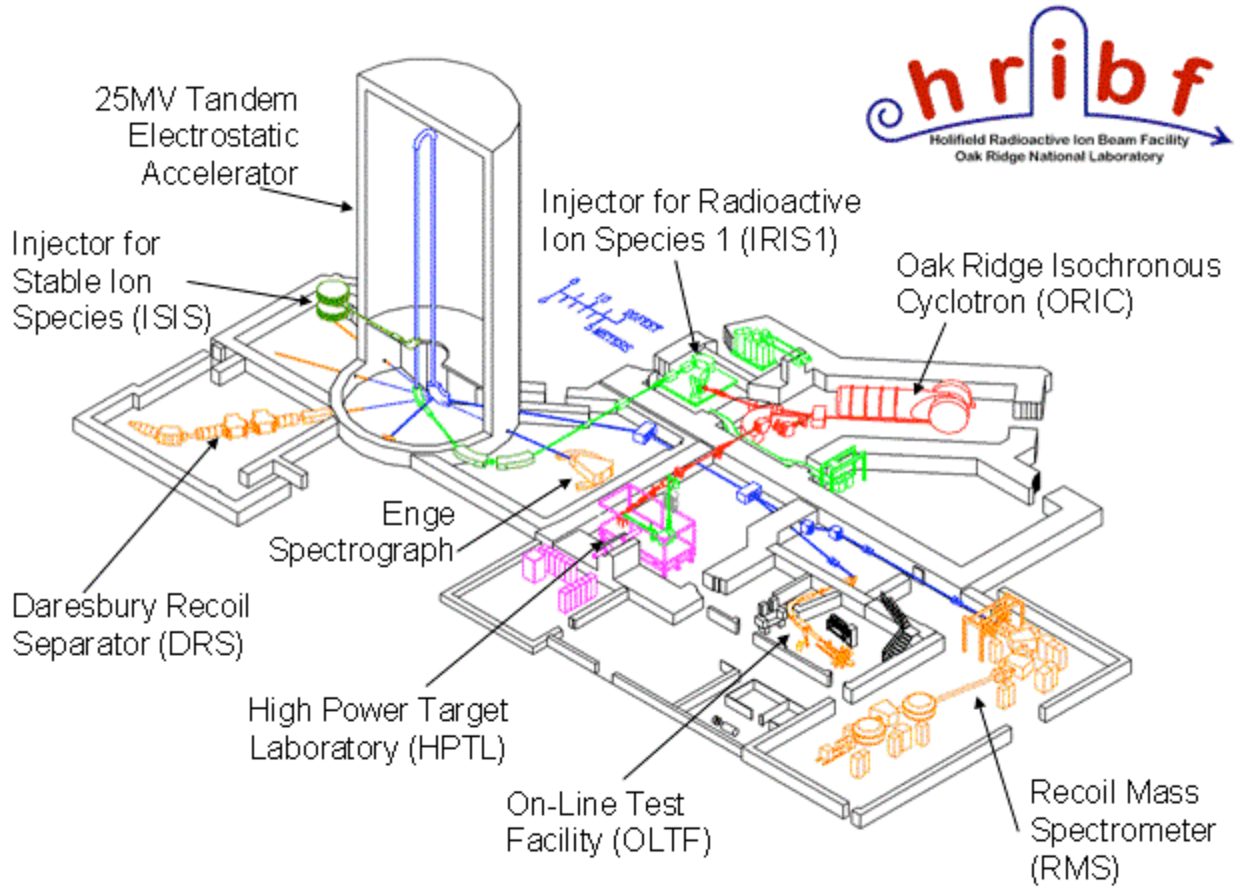

Figure 1. Main components of the Holifield Radioactive Ion Beam Facility (HRIBF).

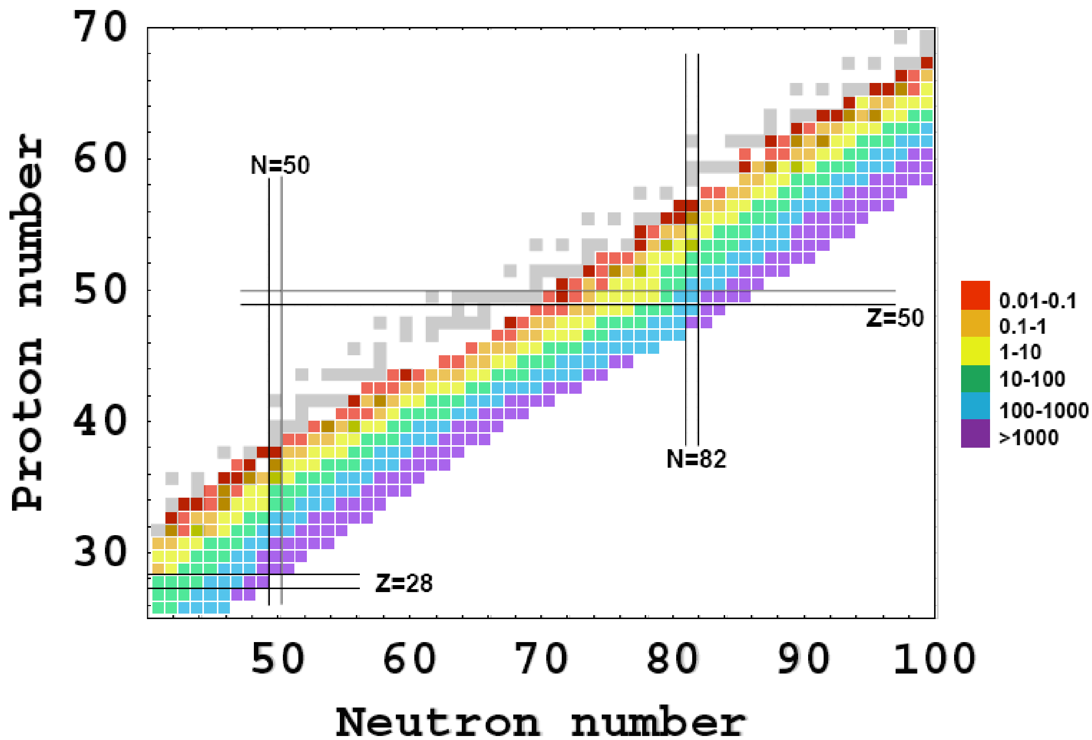

Figure 2. The ratio of the production rate of neutron rich species by thick target bremsstrahlung from 50 MeV electrons to that produced by 40 MeV proton bombardment. The isotopes are produced by fission of ^{238}U. For the electron-induced photo-fission, the beam power is adjusted to achieve 10^{13} f/s (~28 kW of 50 MeV e^- with no converter). The proton-induced fission rate is ~$5x10^{11}$, corresponding to 10µA of 40 MeV p on ^{238}U.

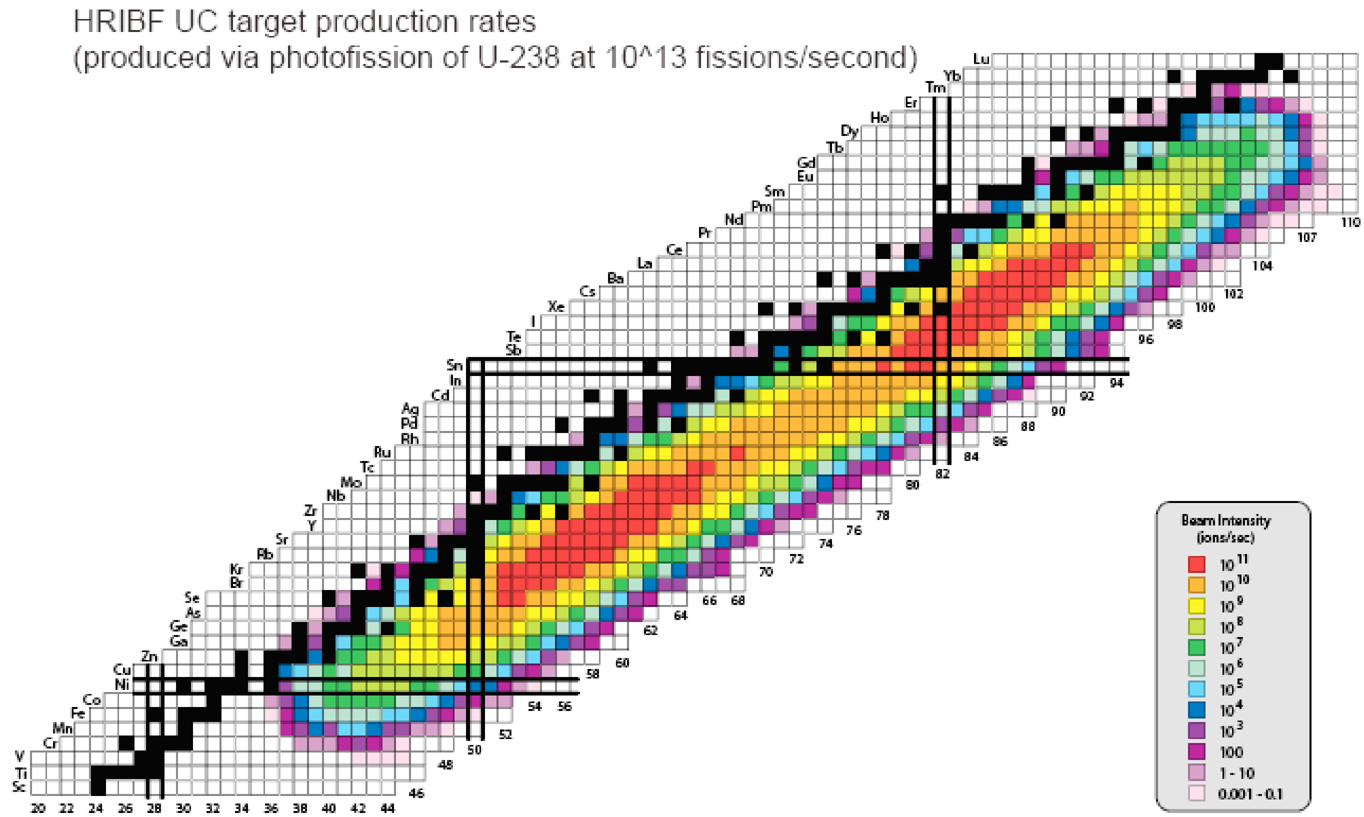

Figure 3. In-target production rates for a total photo-fission rate of 10^{13} /s.

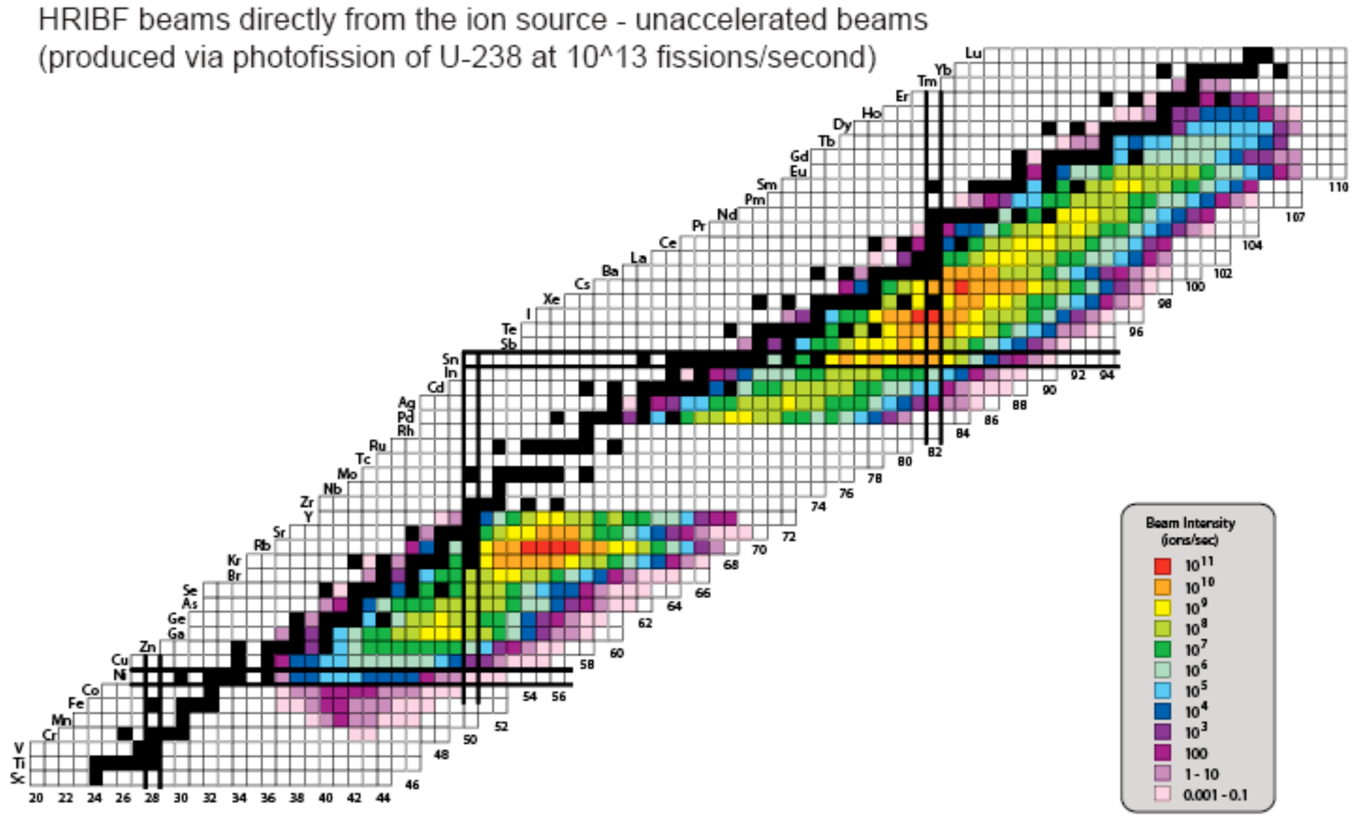

Figure 4. Estimated low energy RIB intensities from a photo-fission facility at 10^{13} f/s.

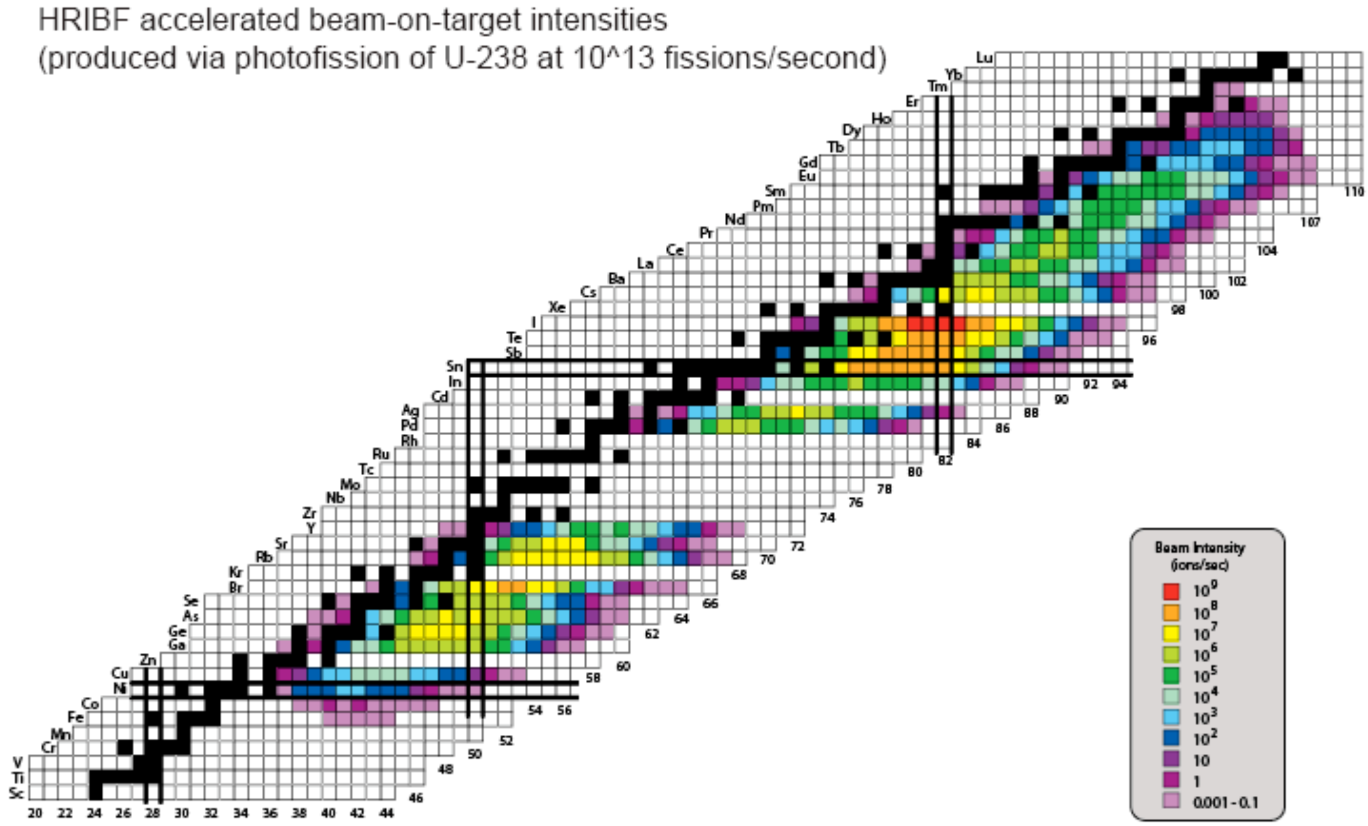

Figure 5. Post –accelerated beam-on-target yields from a photo-fission driver operating at 10^{13} f/s.

Section 2. An Examination of the Viability of Electron-beam Driven RIB Production as an Upgrade to HRIBF

2.1 Introduction

This section is a quantitative examination of the potential of high-power electron beam driven photo fission production of neutron-rich species at HRIBF. It is based on experimental data, experimental systematics [1,2,3], and simulations [4]. The basic conclusions are:

1) Photo-fission rates of 10^{13} f/s can be achieved with beam power ~50kW (E_e = 25-50 MeV), and without assuming significant improvements in target technology.
2) Photo fission rates of 10^{13} f/s correspond to improvements of very n-rich beam intensities in the range 10^2-10^4 compared to present HRIBF performance.
3) Significant issues of the Target Ion Source (TIS) system design and radioactive materials handling remain to be addressed, but no technical breakthroughs are required to achieve the results listed here.
4) High power (~100kW) electron beams of energy 25-50 MeV are the most cost effective path for making several order of magnitude improvements in intensities of very neutron-rich beams at HRIBF.
5) Shielding of the production area, and developing target installation and removal technology and protocols for a photo-fission based upgrade of HRIBF are a significant challenge and are addressed, at least conceptually, in the next sections.
6) Going significantly beyond the mid 10^{13} f/s scale is probably not practical with electron-driven facilities, but such rates can be achieved with facilities based on secondary neutron induced fission. Such facilities are very expensive compared to an electron-driven facility.

The rest of this document presents the material that supports these conclusions. In the next section photo fission is compared to low-energy proton induced fission as a neutron-rich species production technique. Section 3 is a quantitative examination of beam-power requirements and corresponding power deposited in targets for several electron beam energies and target configurations. Section 4 is a brief consideration of radiation, shielding, and radioactive materials issues. Finally some consideration of other means of achieving large intensities of fissure fragment beams is considered in an Appendix. For conveniences only ^{238}U will be considered as the fissioning nucleus. While it is likely that ^{238}U will be the most useful target material, other actinides may be useful for particular beams, and are certainly not excluded.

2.2 Photo-fission vs. Proton induced fission

HRIBF now produces neutron-rich species by ^{238}U(p,f) at proton energies of 40 to 50 MeV. The typical fission rate is ~4 x 10^{10} f/μC. To date beam currents up to 10μA have been used routinely on targets of diameter ~1.4 cm and thickness ~3.9g/cm^2, corresponding to ~6g of ^{238}U in the form of uranium carbide plus graphite with a 4 to 1 C to U atomic ratio. This UC_2 plus graphite mixture will be referred to as UC_4 throughout this manuscript. If we assume the beam power is spread uniformly over the target face (it is probably not very close to this ideal), the maximum power density deposited in the target is ~110 W/g, and the total power is ~350 W. The target thickness is chosen so that incident 50 MeV protons emerge from the target at an energy ~15 MeV, which is approximately the threshold for the (p,f) reaction. The total fission rate now achieved at HRIBF is ~4 x 10^{11} f/s.

As we will see in the next section, a photo-fission rate of 10^{13} f/s is likely to be achievable without significant target developments. The increase in fission rate above present HRIBF practice is about a factor of 25. The corresponding increase in production of the most neutron-rich radioactive species is much more than a factor of 25. This is because photo fission is a much "cooler" process – i.e., occurs at lower excitation energy and consequently results in smaller number of neutrons being evaporated both from the compound system before fission and from the fission fragments. Consequently the production is shifted toward more neutron-rich species. This is illustrated for Sn and Ge isotopes in figure 1. At the same rate of fission induced in a production target, the rate of production of the most neutron-rich Sn and Ge isotopes is more than two orders of magnitude higher. This is equally true for all other species of interest at HRIBF. A plot illustrating the ratio of yields for a 10^{13} f/s photo-fission facility compared to present HRIBF production rates is shown in figure 2 of section 1.

2.3 Beam Power Considerations and Production Rates

Figure 2 summarizes some basic results concerning photo-fission in uranium targets. The heavy solid line gives the fission rate per watt induced in a cylindrical target of dimensions 10 X_0 in length and 3.1 X_0 radius. (X_0 is a radiation length, which corresponds to 6 g/cm^2 for uranium.) Uranium targets currently in use are in the form of uranium carbide mixed with carbon (the overall ratio is roughly four C atoms per U). Targets with good release performance have been manufactured with densities up to 3 g/cm^3, and preliminary results indicate densities up to 6 g/cm^3 present no significant difficulties. The target corresponding to the solid curve is large; a cylinder 20 cm long by 18.6 cm in diameter made of material with a U density of 3g/cm^3. The total U mass is therefore ~8 kg. The performance of a more sensibly sized target (5X_0 long by 1.34 X_0 in diameter) is shown by the dashed (green) line. This target is only 10 cm long by 3 cm in diameter and weighs 212g. The dimensions are similar to targets long in use at ISOLDE. The fission rate is ~2/3 that of the much larger target. Note that the dimensions of the large target (Fig. 2, solid blue curve) are very near saturation. A semi-infinite target shows only a marginally increased fission rate over the energy range covered here. In these calculations, electrons are incident along the axis of the cylinder. Most of the fission rate loss in the smaller target is a result of the limited radial dimension. For reference, the Moliere radius in U is R_M~2.4X_0 so that the radial dimension of this target is only ~0.27 R_M. The 5X_0 by 1.34X_o target exhibits a combination of adequate fission performance, plus size commensurate with fast release. These dimensions, using 3g/cm^3 UC_4 material will be used in all subsequent simulations except as specifically noted.

A very large percentage of the electron-induced fission in the calculation results from absorption of bremsstrahlung photons absorbed in the giant dipole resonance region of the U. The solid and dashed lines of figure 2 result from direct bombardment of the UC_x targets by electrons, so that the comparatively little fission occurs in the front of the target; i.e., the first radiation length or so of the target is used to convert electrons into photons. Consequently, it might be advantageous to interpose some high Z material (which can be cooled aggressively) in front of the UC_4 target to convert electrons into photons. The effect of such an addition on fission rate is shown by the dotted (red) cure in figure 2. As can be seen, it results in lower fission rates, especially for electron beams with energies <75 MeV. This has sometimes led people to the conclusion that it is always better to use direct electron bombardment. One of the basic effects expected from the introduction of a converter is illustrated in figure 3, which shows the depth profile of fission events in a 20 cm long by 3 cm diameter 3 g/cm^3 UC_4 target (integrated over the radial dimension). For 200 MeV electron bombardment, the fission yield peaks at about 5 cm into the target (~ 15 g/cm^2) while with a 2 X_0 tungsten converter, the peak in fission yield is shifted to the front face of the target. Other bombarding energies show qualitatively similar effects.

The upper plot in figure 4 shows the total beam power (solid line) required to achieve 10^{13} f/s in a 10 cm long by 3 cm diameter (3 g/cm^3) UC_4 target as a function of beam energy, and the corresponding total power deposited in the target (dashed line). The lower plot in figure 4 shows the peak power density in the target for the beam required to reach 10^{13} fissions. This power density is obtained from a 1 cm Z (axial dimension) grid, and integrated over the radial dimension. The solid black horizontal line shows the maximum power density demonstrated in practice at HRIBF for extended bombardments with proton beams ~105 W/g. All the data in figure 4 refers to direct bombardment of the target (no converter).

Figure 5 explores the effect of converter material on power deposition. The lower plot shows the initial beam power required to achieve 10^{13} f/s as a function of converter thickness (in radiation lengths). Tungsten is assumed as converter material (tantalum is probably a preferred due to lower activation—but would behave essentially identically in these plots). As expected the addition of converter material in front of the target increases the beam power required to achieve 10^{13} γ/s. For example, at 25 MeV 38 kW is required for no converter but 59 kW for a 1.5 X_0 converter. Note, however, that while the beam power required goes up, the power deposited in the UC_4 target (upper plot) drops, dramatically for 25 MeV electrons and more modestly for higher energies. Figure 6 shows the corresponding peak power densities calculated in the same way as for figure 4. Here the effect is ever more dramatic for the two lower energies explored. The peak power density deposited for 25 and 50 MeV can be brought down essentially to the level already demonstrated at HRIBF by a judicious choice of converter thickness, at the cost of needing more total power in the electron beam. The required beam powers are ~ 50 kW for 50 MeV and ~ 60 kW for 25 MeV. These power levels are easily achieved in a modern electron accelerator producing beams of these energies.

From these simulation results, we can conclude that an electron-beam driven RIB production accelerator for fission fragment beams is feasible, even without advances in target technology. The fact that this can be achieved at energies as low as 25 MeV is important since it opens up an additional turn-key accelerator technology for potential use (the Rhodotron [5]).

It should be noted, however, that complete thermal analyses of targets and converter disks remain to be done. A system driven by 50 MeV electrons has the following properties. If we choose to employ a $3X_0$ converter disk, the beam power required to achieve 10^{13} f/s will be 59.5 kW. The power deposited in the converter will be 36.6 kW, the power deposited in the production target 9.1 kW, and the peak power density 117 W/g. The converter will require aggressive cooling to deal with this power level, but the total power and power density in the production target should not be a problem. Nevertheless finite element calculations should be carried out to estimate the actual temperature distributions. The power density in the production target can be reduced further by interposing low-Z material (C or Al) between the converter and the target material. This material serves to reduce the energy deposited in the target by low energy electrons emerging from the converter disk. For example using a 50 MeV electron beam, a $2X_0$ converter and 4 cm of C, we find that 89 kW of beam power is required to achieve 10^{13} f/s. The power deposited in the converter is 43 kW, and the power deposited in the production target is 11.5 kW. The peak power density in the target is reduced to 68 W/g. It seems likely that the gain made by this addition is not sufficient to justify the additional complexity and the addition primary beam power required.

The fission rate of 10^{13} f/s corresponds to an improvement of a factor of 13 over current HRIBF capability, but as illustrated by figure 1, the real effect on the intensity of the most interesting neutron-rich beams is much larger. Production of interesting neutron-rich species is increased by large factors in the range 10^2 to 10^4. This production-intensity ratio is illustrated in figure 7.

2.4 Radiation and Materials Handling Issues

The most cost effective implementation of electron driven RIB production is likely to be in the form of a 25 MeV Rhodotron [3] or a 50 MeV superconducting CW Linac, with a power capability ~100 kW. The maximum neutron yield from this beam is ~2.5×10^{14} n/s (10^6 R/h at 1 m). The HPTL was designed for a neutron source of 3×10^{13} n/s. Thus the neutron production of an electron accelerator driven facility will be ~10 times larger than HPTL. The effective shield thickness of normal density concrete required to generate a dose less than 1 mr/hr at its outer surface with this source term is approximately 8.5 feet. The dose-equivalent at 90^0 to the incident electron beam due to γ radiation is also estimated to be ~10^6R/h [3]. The shield thickness required to reduce this dose to 1 mr/h is about 13 feet of normal density concrete or 4.25 feet of steel. The highest γ-flux is in the electron beam direction. A 100 kW 50 MeV electron beam incident on a high-Z thick target produces ~ 10^8 R/h due to γ-radiation over a small angle (~4 degrees) with respect to the electron beam. About 16 feet of normal density concrete would be required to reduce this dose to 1mr/h. The high forward dose can be dealt with by directing the electron beam vertically down into the earth. A beam dump, probably consisting of Fe and concrete will be constructed in an excavated volume below the target position. It will probably be necessary to build the entire irradiation area below grade.

Photo-fission is very efficient at producing neutron-rich species. The activity of target materials following an equal time of bombardment should be a factor of ~12-25 larger than with the present facility. The mass of target material activated per bombardment will, however, be about 35 times larger.

2.5 Conclusion:

It has been demonstrated that a facility based on relatively high power (30 to 100 kW) electron beams in the energy range 25-50 MeV can be used to induce fission in a modest-sized UC_4 target at a rate in excess of 10^{13} f/s. This can be achieved with target and ion source technology already available. However, it is difficult to see how this technique, even with major target developments, can be scaled up in yield more than a factor of 3 to 5. Consequently an ultimate limit well below 10^{14} seems certain. Other methods that might be capable of rates in the range 10^{14} – 10^{15} f/s are discussed in Appendix A. These techniques, however, involve investments on the order of hundreds of millions of dollars, as well as significant technical developments. The electron-induced fission option is almost certainly the most cost effective way to reach 10^{13} f/s using a sufficiently cold process to populate the most neutron-rich species effectively. This is largely because the required electron accelerators are comparatively cheap and small. A cost estimate for a 25 MeV dual Rhodotron System capable of delivering >100 kW of electron beam power of ~$9M has been provided. A 50 MeV superconducting electron linac capable of 50 kW has been costed at ~$7M. A production facility based on one of these machines could be grafted on to the existing HRIBF facility for <$20M, including all civil construction. Such a facility would enhance the production yields of neutron-rich species at HRIBF by factors from 10^2 to 10^4, with the larger numbers applying to the more interesting, most neutron-rich nuclei.

ISAC-II at TRIUMF will probably be capable of producing fission rates up to ~ 5×10^{13} f/s using direct bombardment with 100 μA beams of 500 MeV protons on of 30g/cm^3 thick UC_4 targets. This production method will not lead to the enhanced production of n-rich species expected for “cold” processes and illustrated in figure 1, and will consequently be less favorable for production on n-rich species than 10^{13} photo-fissions/s. The 500 MeV proton beam at TRIUMF is capable of substantial production of low energy neutrons by spallation, and hence of “cold” two-step fission. Preliminary estimates suggest a maximum rate less than ~10^{13} f/s and therefore comparable to the upgraded HRIBF.

Spiral II at GANIL will employ ~ 18 MeV neutrons produced by the fragmentation of 40 MeV deuterons to induce fission. This technically challenging project aims at a fission rate of 10^{14} f/s, which will require a beam of ~5 mA of 40 MeV deuterons on a target of mass on the order of 5 kg. This is discussed further in the Appendix 2a.

References

[1] Yuliang Zhao, PhD Thesis, Department of Chemistry, Tokyo Metropolitan University, Jan. 1996
[2] Kazu Tsukada, HRIB Internal Report, 1998
[3] Dan Stracener, Priv. Com.
[3] GEANT Code System, CERN program library

Appendix 2.a

The distribution of final fission products produced by photo-fission of ^{238}U is very favorable (i.e. shifted to greater neutron numbers) compared to proton-induced fission. The distribution is very similar to that produced by neutrons of energy ~15 MeV incident on ^{238}U. Lower energy neutrons (~ few MeV) produce a distribution of products shifted somewhat more toward neutron excess and with a stronger suppression of symmetric fission. The latter effect leads to a reduced yield of elements with atomic number in the range 43 to 49, as well as an order of magnitude suppression of elements with $Z > 60$ or $Z < 30$.

Since charged particle reactions produce hotter compound nuclei, and consequently hotter fission fragments, it can be an advantage to use the charged particles to produce a secondary source of neutrons which, in turn, induces the fission in an actinide target. This two-step procedure offers the even greater advantage of isolation of the energy deposited by changed particles from the RIB production target.

One technique for accomplishing the conversion of charged particles to neutrons is to use a very intense beam of low energy (~40 MeV) deuterons, incident on an aggressively cooled target thick enough to stop the charged particles (e.g. ~7 mm C). The forward yield of neutrons from the thick target interaction is largest, and has the narrowest angular distribution for light targets (Li, Be, C, etc.), but Cu is also a viable option. A 40 MeV deuteron on a thick light target produces a neutron energy distribution peaked at ~ 17 MeV with a FWHM of ~ 18 MeV. The angular distribution is roughly Gaussian, peaked forward with a half width of ~ 13 degrees plus a broad tail with a half width of ~30 degrees. Using a target of the same dimensions and density as that employed for the e-beam calculations (L=10 cm r= 1.5 cm ρ=3 g/cm^3, total mass 212 g), we estimate a total fission rate of 5.3 x 10^9 f/μC. A deuteron beam intensity of 1.9 mA is required to achieve 10^{13} f/s (7.5 kW). The power deposited in the fission target is small—only about 2.7 kW at 10^{13} f/s, and almost entirely due to fission fragments themselves. The power density deposited in the deuteron fragmentation target is, of course, very large indeed. A target of this geometry would require ~19 mA of deuterons to reach 10^{14} f/s.

An accelerator capable of producing 5 mA beams of 40 MeV deuterons is planned for Spiral II at GANIL. This facility is designed to be capable of rates up to 10^{14} f/s. The target proposed for achieving 10^{14} f/s is made of a large number of normal density (11 g/cm^3) UC_2 disks, each ~1 mm thick and 14 mm diameter. These disks are stacked together to form a composite cylindrical target 8 cm long by 7.5 cm in diameter, with a total mass of 5.1 kg. For this target we estimate 2.1 x 10^{10} f/μC, so that, in agreement with the GANIL design, ~500 μA (20 kW) is required to reach 10^{13} f/s, and 5000 μA (200 kW) required for 10^{14} f/s. At 10^{14} f/s the power deposited by fission in the UC_2 target will be ~ 30 kW, and the power density which must be dealt with by the neutron production target will be prodigious, requiring rapidly flowing liquid metal targets or massively engineered rotating solid targets.

Another method of producing neutrons for inducing fission is by spallation in heavy targets (e.g. Hg) using beams of 1 GeV protons. For very large targets (60 cm x 16 cm) large neutron yields up to 30 neutrons per proton can be achieved. A more modest spallation target formed from a mercury jet 4 cm diameter achieves ~15 n/p. Average neutron energies are about 2 MeV with a Maxwellian spectrum. The neutron angular distribution is isotropic within a factor of 2. The production target in such a system would consist of a uranium blanket ~ 3 cm (~18 g/cm^2) thick surrounding the neutron production target. The U target mass could range from 30 kg to more than 100 kg, depending upon the configuration. Such a system should achieve fission rates of ~ 10^{15} f/s using MW scale 1 GeV proton beams, but release and transport of the fission fragments to an ion source (our sources) is bound to be challenging.

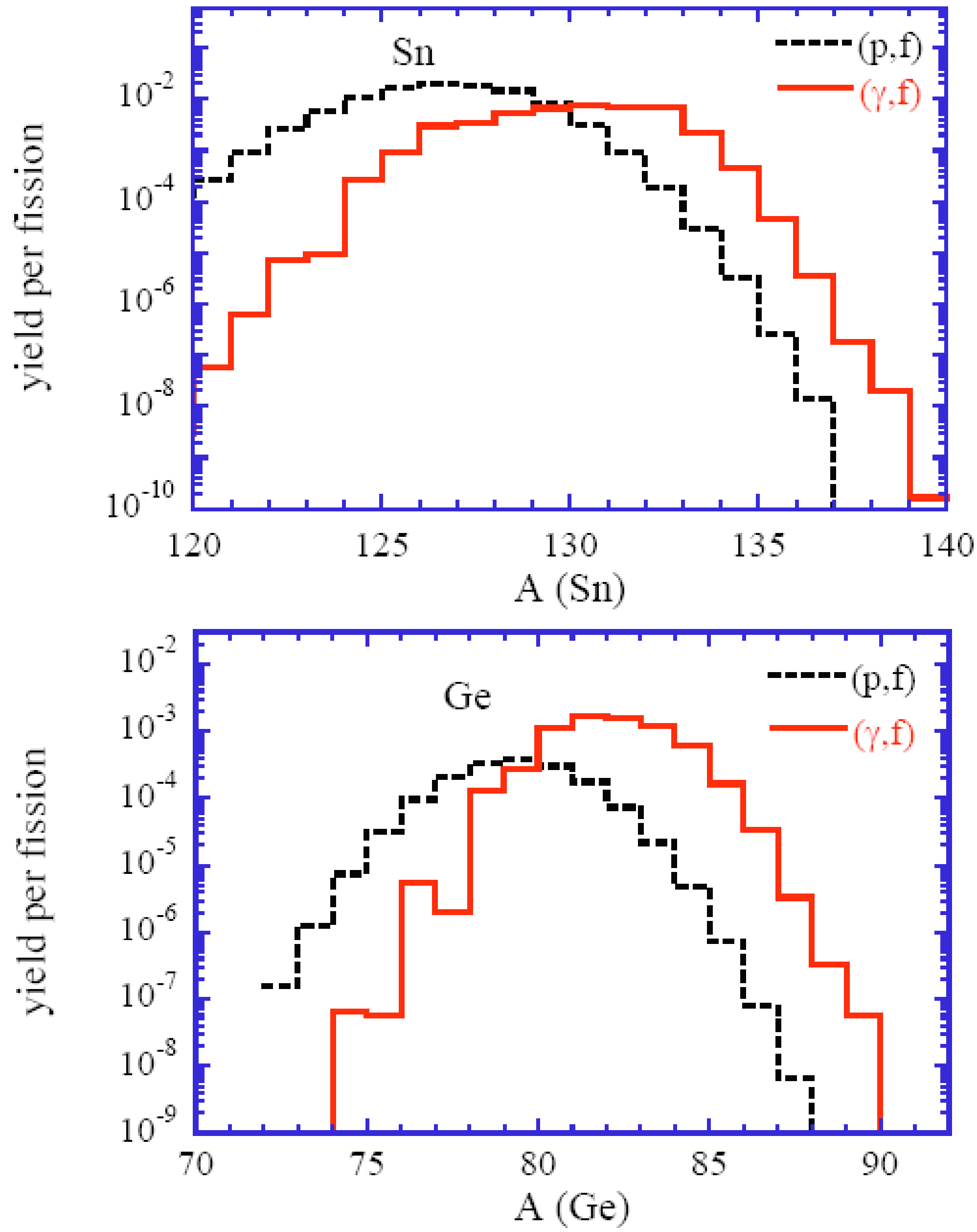

Figure 1. Comparison of yields of Sn and Ge isotopes produced by bremsstrahlung-induced photo-fission (solid red line) and 40 MeV proton induced fission (dashed black line) of ^{238}U

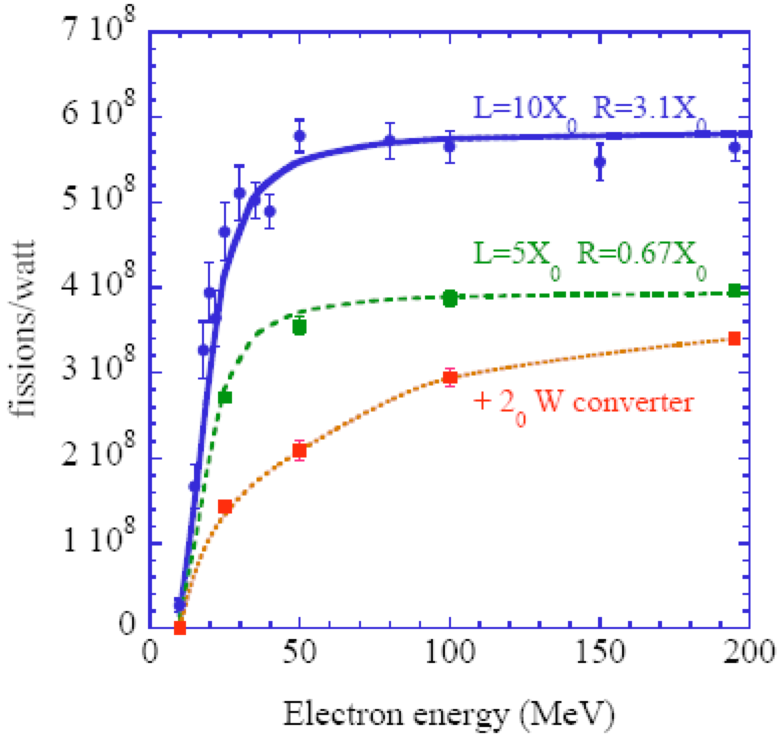

Figure 2. Fission rates for electron beam induced photo-fission of ^{238}U for three different configurations. 1) a cylindrical target 10 radiation lengths (X_0) long by 6.2 X_0 in diameter (blue solid line and filled circles). 2) a cylindrical target $5X_0$ long by 1.34 X_0 in diameter (green dashed line and filled squares). 3) same as 2 but with a $2X_0$ thick W disk positioned in front of the target, serving as a converter (red dotted line and squares). X_0 for U is 6 g/cm^2, and for W is 6.8 g/cm^2. For reference, the Moliere radius in U is ~$2.4X_0$.

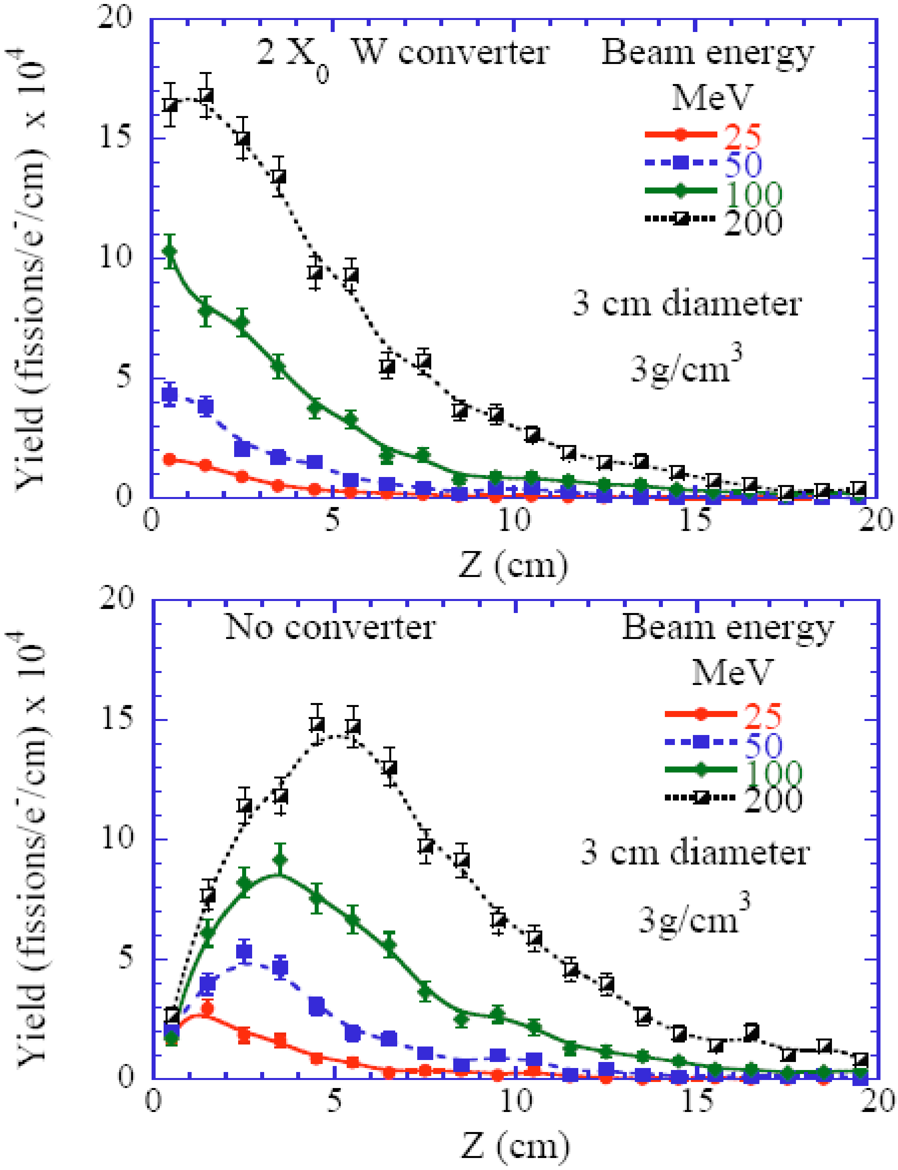

Figure 3. Depth distribution of electron beam induced photo-fission events in a cylindrical target 3 cm in diameter and 20 cm long made of 3 g/cm^3 UC_4. The lower panel corresponds to direct electron bombardment of the target. For the upper panel an additional $2X_0$ W disk was placed directly in front of the UC_4 target.

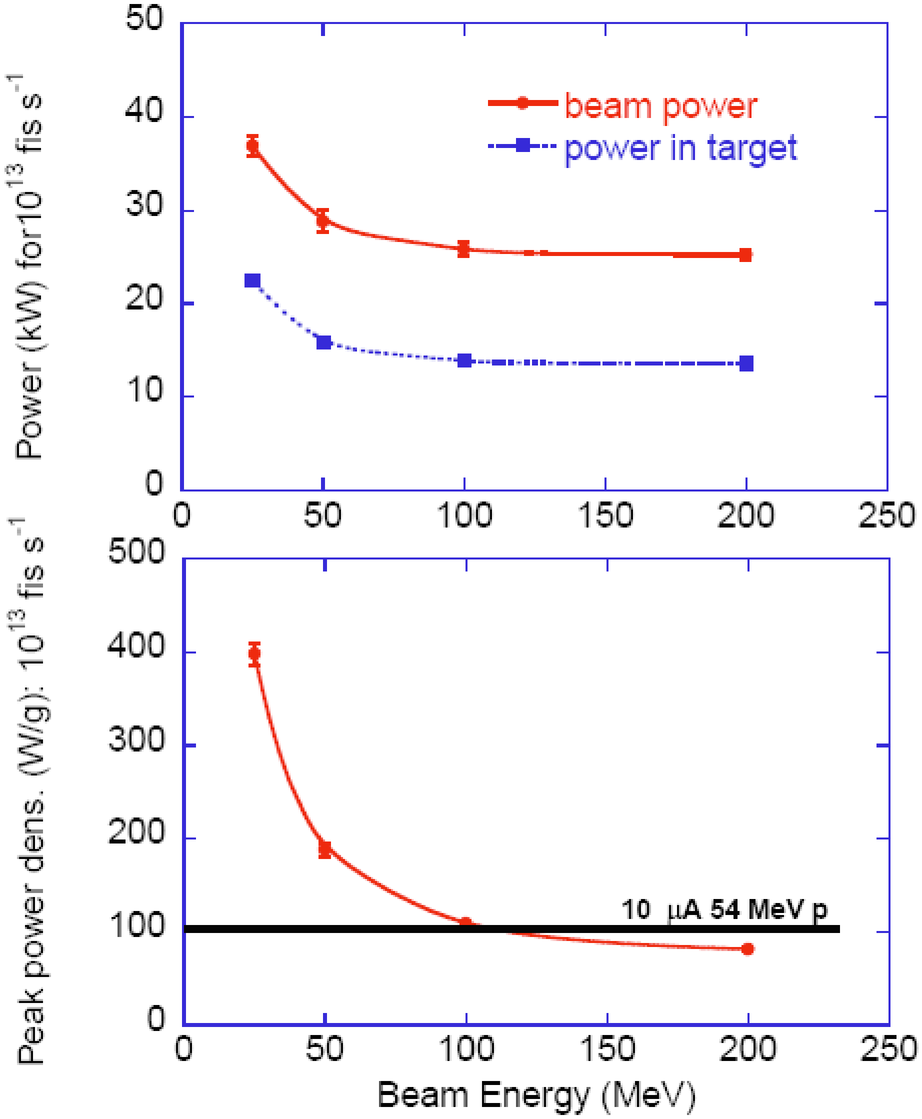

Figure 4. Beam power and target power deposition effects as a function of electron-beam energy. For both panels the electron beam intensity is adjusted, at each energy to produce 10^{13} f/s. The upper panel shows the beam power required (red solid line) and the corresponding total power deposited in the target. The lower panel gives the local maximum power density deposited in the target. The target is the standard $5X_0$ long by $1.34X_0$ diameter $3g/cm^3$ UC_4. The maximum power density routinely used in proton bombardment at HRIBF is shown as a black horizontal line in the lower panel.

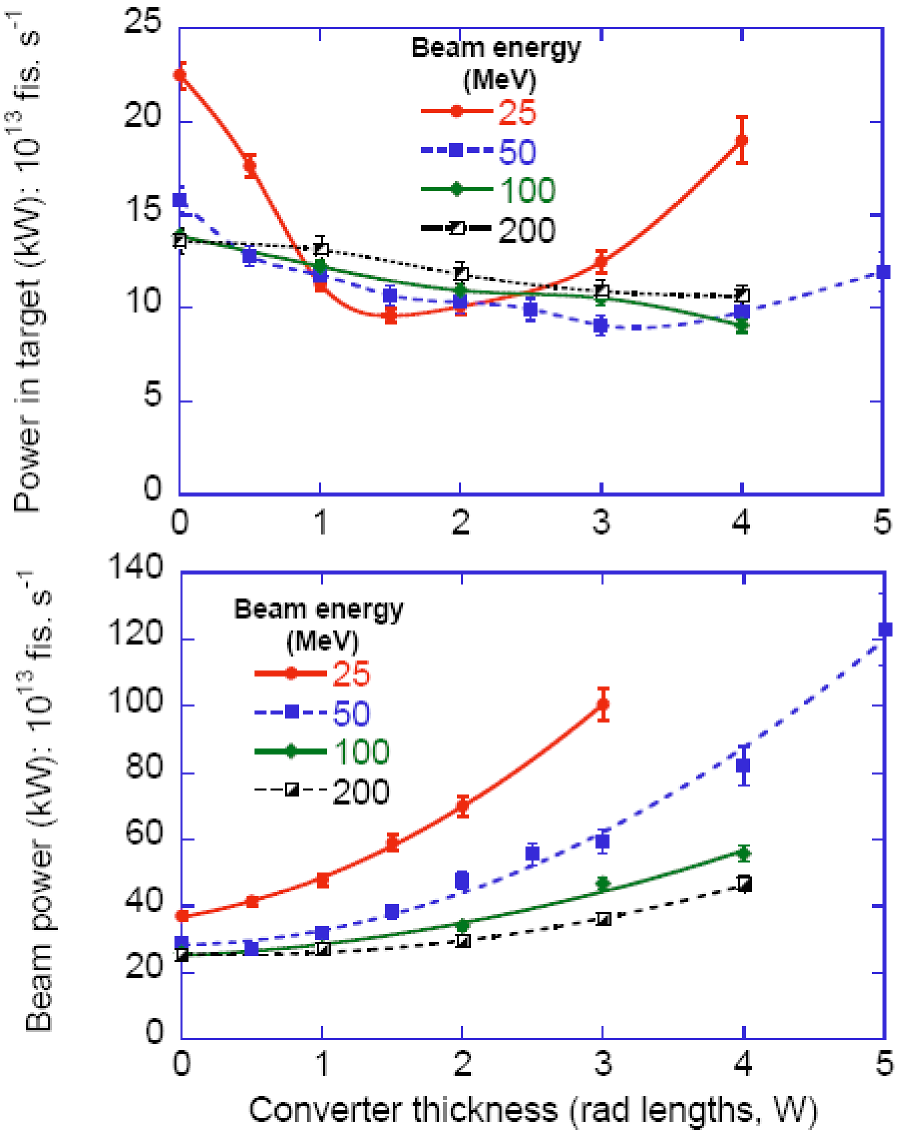

Figure 5. The effect of W converter material on beam power requirements and power deposition in targets. The target is the standard $5X_0$ long by $1.34X_0$ diameter $3g/cm^3$ UC_4. The lower panel shows the electron beam power required to produce 10^{13} f/s as a function of energy and converter thickness. The upper panel shows the corresponding variation of power deposited in the target.

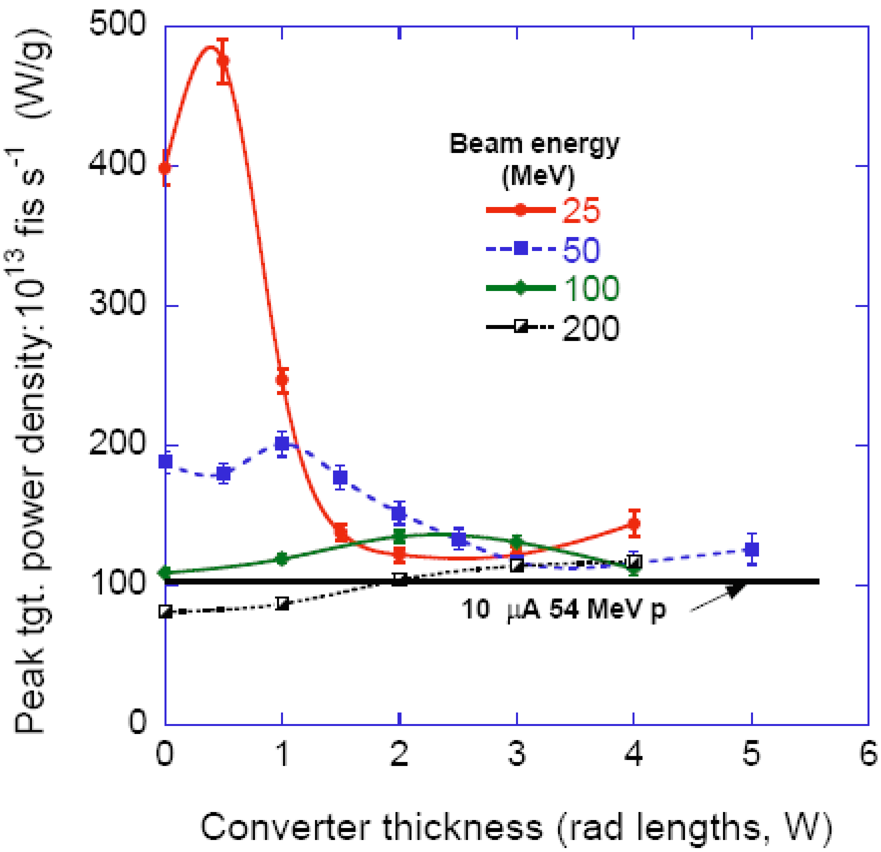

Figure 6. The maximum local power density deposited at the beam powers required to achieve 10^{13} f/s (shown in figure 5). The black horizontal line refers to the power density routinely reached in current HRIBF targets.

Section 3. The Driver Accelerator

3.1 Introduction

Photofission and photoneutron production are produced by Bremsstrahlung photons of energy near the peak of the Giant Dipole Resonance of the target nucleus. For uranium, most of the cross section occurs for photons between 10 and 20 MeV, as shown in Figure 1 [1]. Bremsstrahlung is produced as a continuous spectrum of photons with energies that start at the energy of the electron, with near zero yield, increasing in intensity as the energy decreases. Figure 1 also shows the Bremsstrahlung yield from 20.9 MeV electrons on a thick, heavy target referenced to the right-hand y-axis [2]. At low energies, self-absorption in the target reduces the number of transmitted photons. The photofission yield is given by the integral of the photofission cross section and the number of Bremsstrahlung photons of a given energy, over the total energy range of the photofission cross section or the Bremsstrahlung energies if they peak at below about 30 MeV. This results in saturation in the yield per kW of electron beam power of both photoneutrons and photofission for electron energies above about 50 MeV. Even for 25 MeV electrons, the yield is nearly 80% of the saturation yield. This is illustrated in Figure 2, taken from Section 2, that clearly shows the saturation in yield for electron energies around 50 MeV. Because of this, a driver accelerator for the proposed upgrade can be any electron accelerator capable of at least 25 MeV electrons and beam powers of about 50 to 70 kW.

3.2 Electron Accelerators

3.2.1 Electron Linacs

An electron linac is one alternative for obtaining the desired driver beam. Non-superconducting options exist from commercial manufacturers such as Accel. Although they can provide a 50MeV, 200mA turnkey linac for around $5M U.S. dollars, the beam is pulsed and less desirable than a CW machine which would reduce the likelihood of thermal stresses in the RIB targets. Superconducting near-CW commercial linacs can also be obtained, but for a much higher price.

There have been several proposals from existing accelerator facilities for superconducting electron linacs that can reach between 40 and 50 MeV with the required beam power. The GANIL proposal [3] for the electron beam option for SPIRAL II had done a conceptual design of a 45 MeV linac. This is shown in Figure 3. The beam current required for 60 kW is less than 1.5 mA and should be readily obtained. The front end is a conventional thermionic cathode and a 100 keV electron gun. The GANIL proposal estimated that this would cost about 6 million Euros plus the cost of the personnel to complete the development. The approximate size of the linac is shown on the figure.

Figure 4 shows a proposed design by A. Todd [4]. It uses a single graded-β superconducting cavity as a capture section cavity. This cavity is included in the main cryostat with the main accelerator cavities to both save length and cost. The electron gun is a laser-driven photocathode gun, a more complex design than the thermionic gun proposed for use in the SPIRAL II linac. These changes would reduce the length and some associated costs such as building costs compared to the design in Figure 3. This proposal is for a very high current design for a free electron laser. R. Kazimi, of the Thomas Jefferson Laboratories has produced a similar design aimed at a 50 MeV, 1.2 mA electron beam [5]. The estimate of the cost of that linac was less than 7 million US dollars, plus the cost of the cryogenics.

3.2.2 Rhodotron Accelerators

In addition to linacs, there exists a very compact electron accelerator manufactured by Ion Beam Applications (IBA). The IBA Rhodotron accelerator [6] is a non-superconducting recirculating accelerator that operates in continuous mode and is capable of high beam power, high electrical efficiency, and low maintenance costs. IBA presently manufactures a 10MeV Rhodotron with beam power up to 700kW. Approximately 17 of these accelerators are in service around the world and are typically used for medical sterilization and mail irradiation.

Although a single 25 MeV Rhodotron could be designed with significant development cost and some technical risk, IBA proposes to couple two 12.5MeV machines in series to achieve the desired output. The design is based on a slightly scaled version of their model TT200 unit which delivers a 10MeV, 80mA electron beam. A cutaway view of a Rhodotron is shown in Figure 5 and the principle of operation is depicted in Figure 6. A representative layout for the HRIBF application is presented in Figure 7.

The Rhodotron consists of the following major components: electron gun, RF power source, accelerating cavity, external deflection magnets, vacuum system, control system, and a beam transport system that includes a 270 degree vertical bending magnet and scanning horn. In the single room-temperature coaxial-shaped rf cavity, the radial electric field oscillates at 107.5 MHz. Electrons are fired into the cavity accelerated by the electric field. As they emerge from the other side of the cavity, they are reintroduced into the cavity by an external deflection magnet. This process repeats for approximately 10 passes through the cavity with the beam traversing a rose pattern ("rhodos" means rose in Greek). The standard bean transport configuration is for the beam to be bent vertically downward for scanning objects on a conveyor, and this is also highly desirable for RIB production, allowing the earth to serve as radiation shielding.

IBA has provided a budgetary quotation of $9.6M U.S. dollars for a turnkey system that would be designed, manufactured, installed and commissioned at HRIBF in 25 months from receipt of order. Facilities presently operating Rhodotrons indicate that they are quite robust and reliable with greater than 90% up-time. Electrical efficiency is between 25% and 40%, making them very economical to operate. A typical operations and maintenance staff consists of three technicians and no accelerator physicists or engineers. IBA also offers bi-annual on-site maintenance contracts.

3.3 Summary

One of the important aspects of the proposed approach of using an electron accelerator as the new driver is that it is not a significant technical development to deliver the required electron-beam energy and power to produce 10^{13} fissions per second in a conversion target. The cost of any of the potential electron-driver accelerators is roughly the same (around 10 million dollars). This is significantly lower than a cyclotron or deuteron linac that could produce comparable fission yields. The superconducting technology is by now, well established with a very successful operations record and could be readily adapted to this task. The preferred approach is to use the Rhodotron accelerators. They have already been designed for simplicity of operation in an industrial environment and should require the least new support staff. The designs of the superconducting linac are proposed by researchers at laboratory with strong technical support in the technology. If superconducting technology were to be used at Holifield, some technical expertise in cryogenics and superconducting rf technology would be required in both the operations and technical staff. Because of the preference for the Rhodotron accelerator, the layouts of the facility and the converter target and ion source have been developed around a Rhodotron driver. However, the 45 MeV linac proposed for the SPIRAL II project has also been tested in the proposed layout and it can be made to fit within the limited area available for the project with minor changes in the actual facility design. The building costs would be similar.

3.4 References

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[2] A.A. O'Dell, C.W. Sandifer, R.B. Knowlen and W.D. George, Nucl. Inst and Meth. **61** (1968) pp. 340 – 346.
[3] SPIRAL II Project (Electron Option), Preliminary Design Study, GANIL/SP12/007-A.
[4] A. Todd et al., High-Power Electron Beam Injectors for 100 kW Free Electron Lasers, Proceedings of the 2003 Particle Accelerator Conference
[5] R. Kazimi, Presentation on Thomas Jefferson National Accelerator Facility Website.
[6] IBA – website, product description, and maintenance manuals -

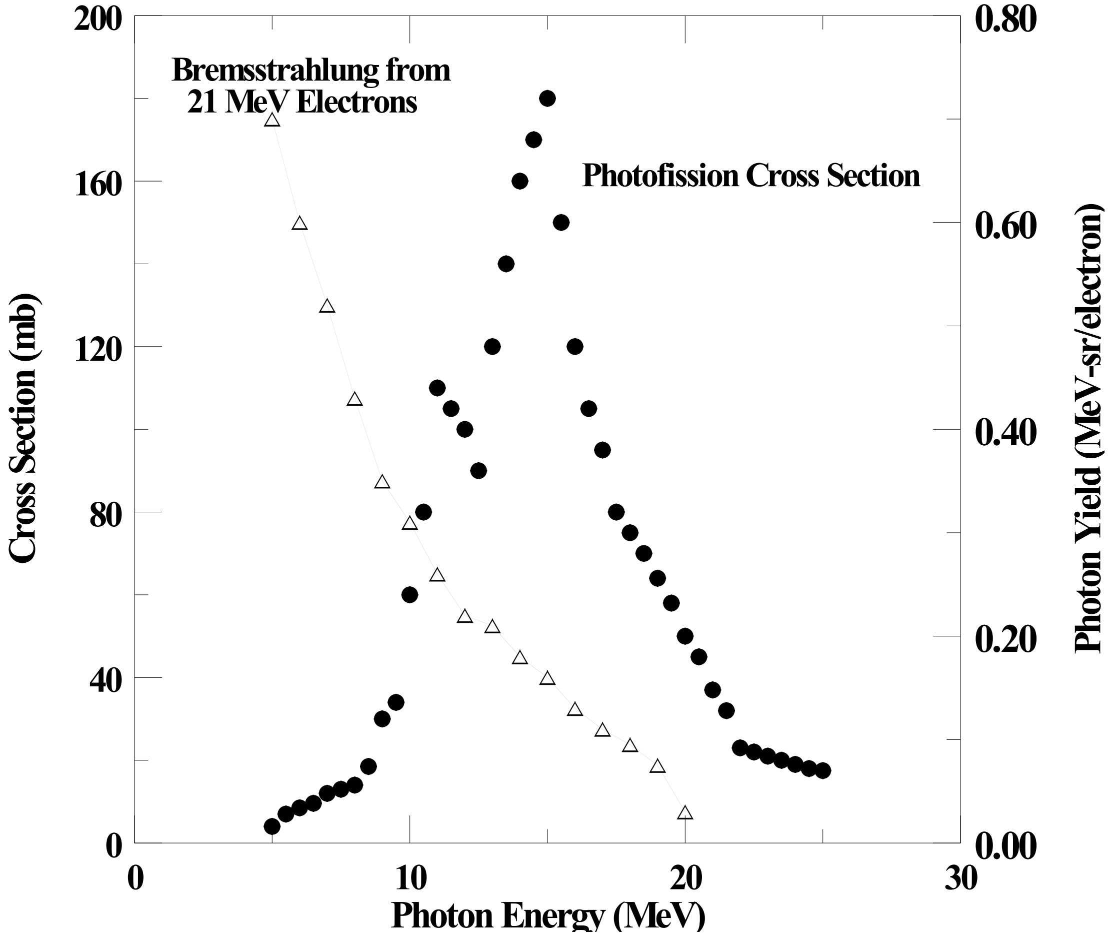


Figure 1. Photofission cross section [1] (left-hand y-axis) and Bremsstrahlung yield from 20.9 MeV [2] electrons on an intermediate thickness heavy converter target.

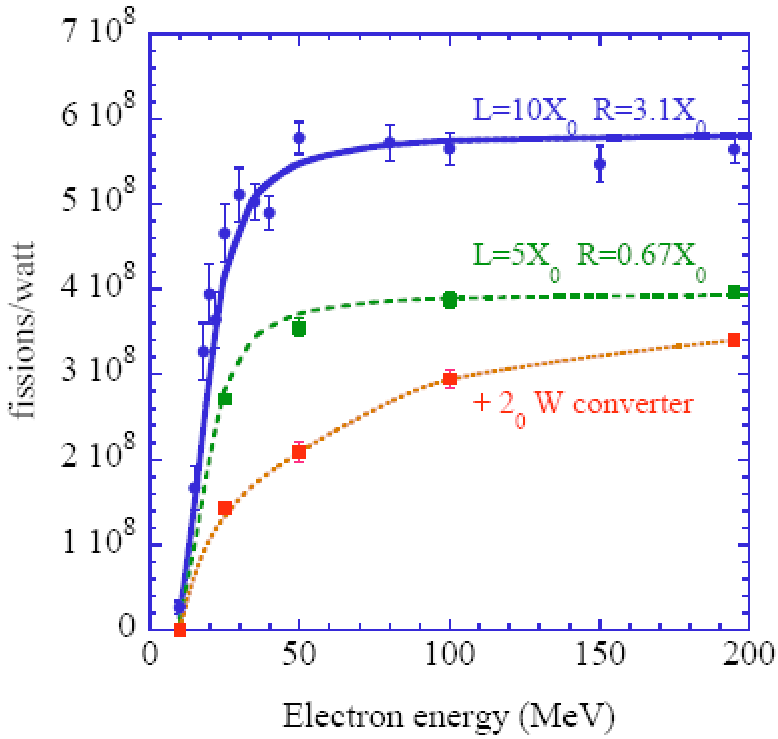


Figure 2. Fission rates for electron beam induced photo-fission of ^{238}U for three different configurations. 1) a cylindrical target 10 radiation lengths (X_0) long by 6.2 X_0 in diameter (blue solid line and filled circles). 2) a cylindrical target $5X_0$ long by 1.34 X_0 in diameter (green dashed line and filled squares). 3) same as 2 but with a $2X_0$ thick W disk positioned in front of the target, serving as a converter (red dotted line and squares). X_0 for U is 6 g/cm^2, and for W is 6.8 g/cm^2. For reference, the Moliere radius in U is ~$2.4X_0$.

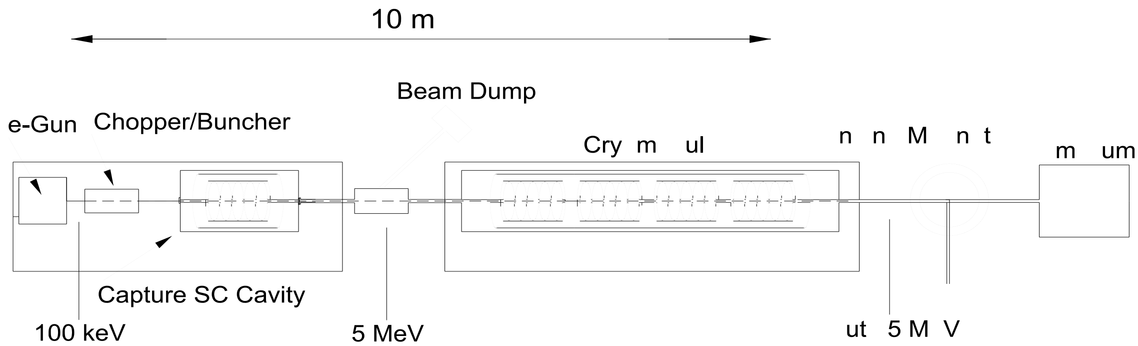


Figure 3. Layout of a superconducting linac proposed for the electron beam option of SPIRAL II at GANIL [3]. The beam current required for 60 kW is les than 1.5 mA and should be readily obtained. The front end is a conventional thermionic cathode and a 100 keV electron gun.

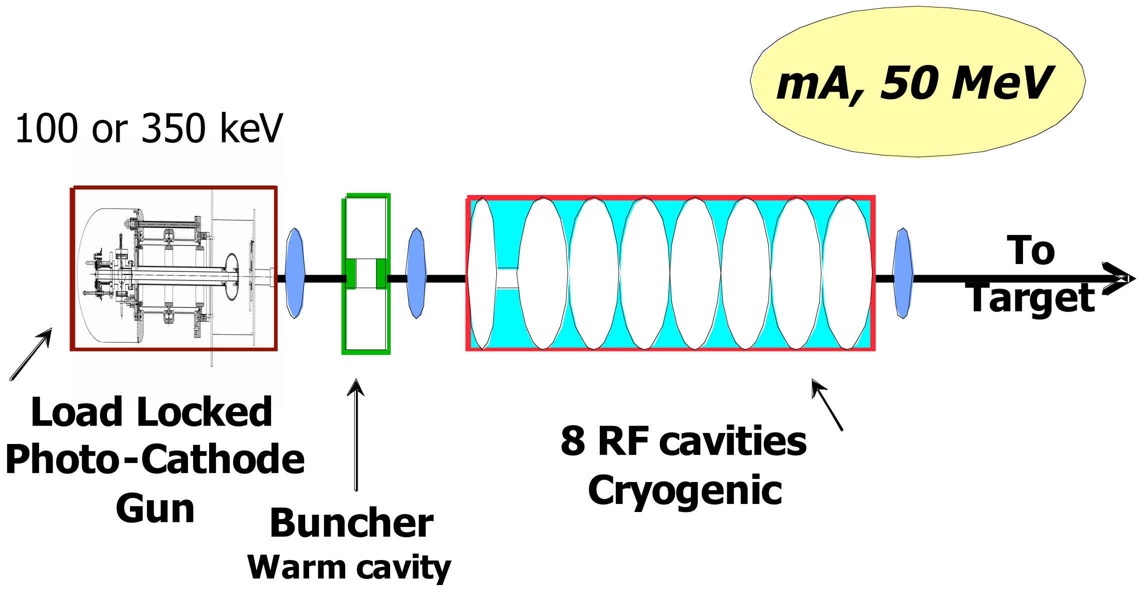


Figure 4. Compact 50 MeV superconducting electron linac proposed by Todd [4]. It uses a capture section cavity as part of the cryogenic cavities, in the same cryostat as the main cavities and a photocathode electron gun. These changes would reduce the length and some associated costs such as building costs compared to the design in Figure 3.

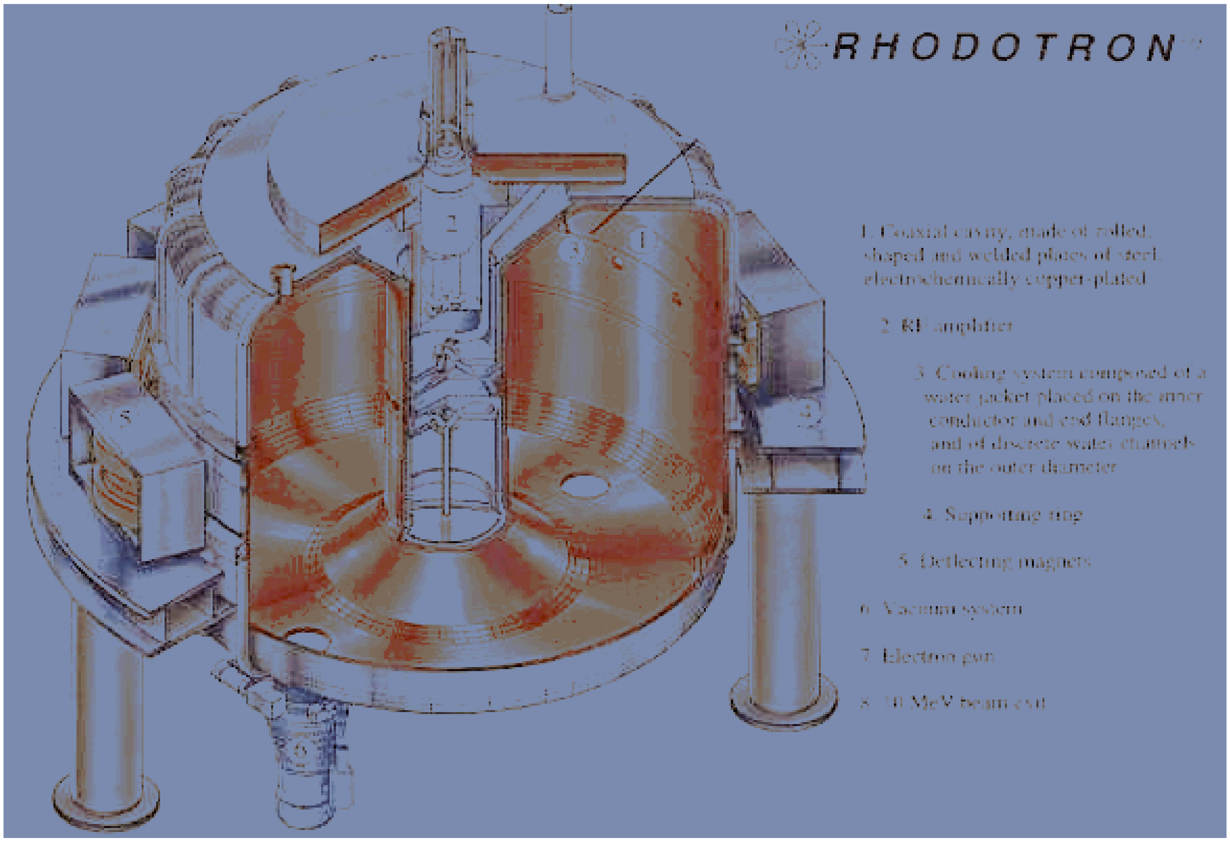


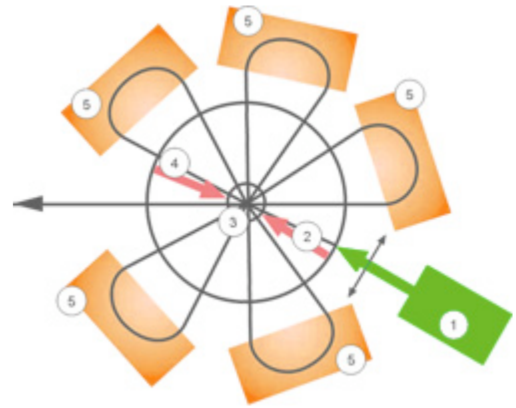
Figure 5. The Rhodotron accelerator built by IBA. The Rhodotron accelerator uses a single room-temperature rf cavity and accelerates the beam across the cavity multiple times via magnets outside of the cavity.

1 - Electrons are fired by the heated filament of the electron source located at the outer wall of the cavity (1).

2 - The electrons are introduced into the cavity when the electric field is such that it will accelerate the electrons inwards, towards the hollow coaxial cylinder in the center.

3 - The electrons pass through openings in the inner cylinder while the electric field is reversing

4 - On emerging from the inner cylinder, the electrons are further accelerated (towards the outer cavity wall) under the influence of the new reversed field.



5 - Using beam deflection magnets, the electrons are reintroduced into the main body of the accelerator for additional crossings of the cavity in order to reach the required energy level and leave the cavity through a beam line (**6**).

Figure 6. The Rhodotron operating principle.

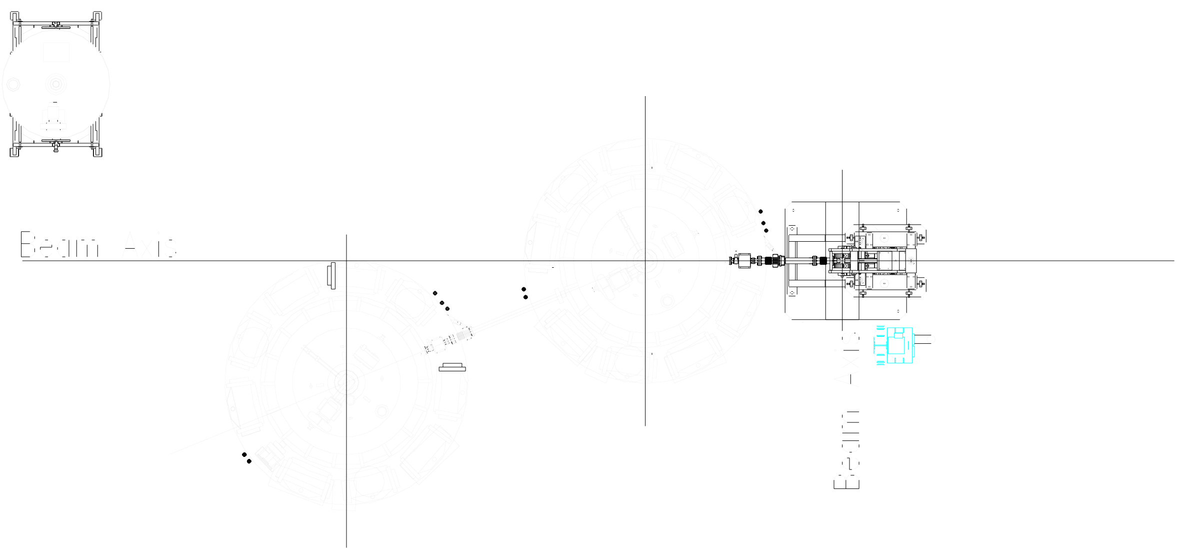


Figure 7. Proposed layout of two Rhodotron accelerators.

Section 4. The Converter Target and Ion Source

4.1 Introduction

In any design of a radioactive ion beam facility, one of the major challenges is in the design of the converter target and ion source and also the initial selection and acceleration of the radioactive species. Typically, most converter targets are designed near the limits of power density of some part of the target. Higher power densities and target-material temperatures generally increase the yield of most radioactive species. This section of the facility is also where the most severe radiation problems generally occur. These issues generally couple to safety issues that must be addressed from the beginning of a project.

The converter target and ion source will be mounted on a plug module following the successful approach developed by the TRIUMF ISAC facility. The plug modules contain the components that are required to intercept the driver beam, the ISOL ion source and the initial beam selection components. The plugs both contain the components and provide the initial shielding between the interaction region and the location required to service the equipment. A high-power electron beam is capable of producing very high yields of Bremsstrahlung radiation and also high fluxes of photoneutrons that can produce activation of the shielding and other material at a significant distance from the interaction point. Thus both the design of the target-ion source and the shielding and its relationship to facility safety must be considered in the design concept.

4.2 Plug Module Concepts

The driver electron beam could be directed either vertically or horizontally into the target plug – there are a number of advantages for either approach. One of the strongest arguments for bringing the beam in vertically is the required shielding in the forward direction for the Bremsstrahlung beam. Figure 1 shows the thick-target Bremstrahlung yield from a high-Z target in both the forward direction and at 90^o [1]. The y-axis is given in rads/h at 1 m from the target for one kW of electron beam power. For 50 to 75 kW of beam power the numbers are appropriately scaled. Figures 2 and 3 give the attenuation of Bremsstrahlung radiation for concrete (Figure 2) and steel (Figure 3) shielding. In order to reduce the forward radiation to a few mR/h, appropriate to areas occupied by facility staff that are Radiation Workers, the thickness of concrete required is more than 4 meters. The radiation yield at 90^o is reduced by about a factor of 100 and it has a much softer energy spectrum [2], that is, the average photon energy is considerably lower, reducing the shielding attenuation by nearly three orders of magnitude.

Starting from this initial assessment of the required shielding, the decision has been made to direct the electron beam vertically into the plug. This leads to the requirement of removing and installing the plug/plugs horizontally and does not permit the use of an overhead crane for this operation. At least two separate plugs or one very large and complex plug will be required. It is proposed to use two and likely a third small plug with beam-transport elements to steer and focus the beam as it passes through the walls of the new facility before further correction can be applied. One plug will contain the converter target to intercept the electron beam and produce the Bremstrahlung radiation and the ion source that will be required to operate at 30 kV or greater with respect to a grounded extraction electrode. A second plug will be developed that contains the initial optical elements and a Wien filter to provide the initial mass selection. The initial concept is to contain the two large plugs in a common vacuum vessel. Figure 4 shows an initial concept of this plug. The vacuum box is shaded to indicate its extent. Two separate plugs are used. The electron conversion target and the ion source are mounted on one plug and the extraction aperture, optical elements and a Wien filter and slit are mounted on the second plug.

4.2.1 Converter Target and Ion Source Plug

Figure 5 shows further details of the conversion target and ion source plug. They are both mounted on a plate that is electrically insulated from the walls of the plug with three ceramic insulators under the ion-source support plate. The outside of the plug is a grounded shell that is vacuum tight except at the apertures permitting the electron beam and RIB beam to enter or leave the enclosure. In order to restrict circulation of contamination in the case of a catastrophic failure of the RIB target or converter target, two fast (less than 10 ms) shutters are used over the two apertures into the box. Thick steel radiation shielding is also mounted on the local high-voltage deck to shield the front of the plug from the intense radiation. The electrical leads and water-cooling lines to the source and converter target are mounted on a large cylindrical insulator and fed to the internal high-voltage deck and threaded through the shielding to avoid, as much as possible, line-of-sight from the target. This is illustrated schematically by the shading of the metal shielding in one view. Because the plug is inserted horizontally, there are wheels on the bottom plate that guide the plug to the installed position. The electron beam is directed through a hole in the top of the plug to the conversion target just in front of the fission target. The radioactive ion beams are extracted from a source aperture on one side of the plug.

Figure 6 shows a concept drawing of the Bremsstrahlung conversion target. This has been modeled, as closely as can be done at the reduced dimensions required for this application, on the neutron target that has been used at the Oak Ridge Electron Linac Accelerator (ORELA) facility. That target is at least 10 X_o thick and has been used to intercept up to 50 kW of electron beam power to produce neutrons for the long life of that facility. Two options are shown in Figure 6. The upper version requires that the water tube be returned to the side of the target, but it reduces the insertion distance between the converter target and the fission target. The lower version is a closer model to the ORELA target. The electron beam passes through the aluminum front window and interacts with Tantalum sheets of increasing thickness that serve as the converter that is approximately 2 X_o in this figure. The Tantalum sheets are captive in machined slots in the aluminum housing and have space between each sheet for water cooling. Detailed thermal analysis will be required to complete this design – the converter target is one of the key interaction points in the system. The electron beam will be scanned with an electromagnetic scanner to cover the area of the converter target as uniformly as possible. If areas greater than shown in this figure are required, a larger converter target can be used and a greater scanning area covered. This would lead to a modest increase in the fission target area.

There are several different ion sources that will likely be used in this facility. Need some ion source discussion

The initial design goal of the insulated ion source and converter target is to withstand 30 to 40 kV with respect to the grounded shell. The insulators and the spacing between the deck and the grounded shell are very conservative in the chosen dimensions. The insulators are shielded from the direct radiation by some of the steel shield. However, it is recognized that the intense Bremsstrahlung radiation will make it difficult to withstand high voltages. There is room in the design to add coaxial electrostatic shields, one from the grounded end and the other, at a larger diameter, from the high-voltage end. These would reduce the impact of scattered charged particles from charging the insulator surfaces that can lead to breakdown. It is also proposed to test mockups of various geometries in the high radiation field of an electron accelerator during early R&D in support of this proposal.

4.2.2 Beam Extraction Plug

An initial layout of a facility addition consisting of two Rhodotron accelerators and a target and extraction plug placed in the preferred location at the Holifield site has been done (see Section 5 for details). The amount of space available is quite limited. The first trial layout used two deflecting magnets to select and transport the beam from the RIB source into a beam transport through the new facility wall and into the existing facility. It was very challenging to fit the required hardware and shielding into the location. The second approach has been to adapt the same technique that was adapted for the SPIRAL II RIB selection system [3]. An ExB or Wien Filter is used to do an initial mass selection right after the ion source module. Figure 7 shows a near copy of their system mounted on a horizontal plug. This plug, like the ion source plug, is built on a rigid base with strong metal wheels to permit it to be installed horizontally into the vacuum box. It contains the Wien filter magnet and slits and entrance optical elements. Most of the radioactive fission fragments from the ion source will be stopped in the slits and they will remain very active after completion of a run. Because of this, the plug will also be vacuum tight but the initial thought is to use radiation hardened valves that close in about one second rather than the fast shutters used for the target plug. This will be considered in more details during a detailed safety assessment of the facility.

4.2.3 Vacuum Box

The vacuum box contains the two plug modules and must also provide for the initial alignment of the beam centerline components. Figure 8 shows the basic design of the vacuum box. The initial concept is for heavy vessel walls, possibly with channels welded along some surfaces as stiffeners. The base is welded to two strong I-beams that support and will also be part of the basic alignment of the vacuum box. Tracks will be machined into the base of both sides to guide the plugs into their final position. The vacuum box will have its own pumping system, presently proposed to exit from the back of the vacuum box and after passing through a maze in the concrete shielding, to reach the vacuum pump at the main floor level of the Rhodotrons.

4.2.4 Remote Handling of Ion Source Plugs

Continued operation of the converter target and ion source will lead to very high levels of radioactivity and the potential of serious contamination problems. This will be considered in more detail in Section 6. The choice of directing the electron beam vertically into the converter target leads to the requirement to install the plugs horizontally. This means that an overhead crane cannot be used to remove or install the plugs, at least not into their operating positions. Since a plug manipulation system must be designed to install and withdraw each plug, a significant effort has been made at an initial concept of a remote installation procedure, at least for the ion source plug. The vault that contains the source plug-handling equipment will be below the main floor to provide shielding from the photoneutrons from the conversion target. The ion-source handling equipment will be located in that vault.

Figures 9 through 13 show these initial ideas. The ion source plug and Wien filter plug are initially mounted in the vacuum box. The first step is to remove the water, power and signal connections to the source and store these in the plug services corridor that is parallel to the ion source vault. Once the vacuum system has been vented, the front flange is released remotely as shown schematically in Figure 10. The upper figure shows the front flange of the vacuum box with both plugs installed. In order to have a smooth transition as the support wheels of either plug carry the load out of the vacuum box and into the storage box it is advantageous to remove the vacuum flange and store it out of line with the plug. Both vacuum flanges are designed to make a vacuum seal with O-rings on the vacuum box and also to make a vacuum seal with the front of the appropriate plug by pulling the plug into its final position with fasteners that are connected to the front plate of the plug. There is an O-ring on the front of each plate that is positioned outside of the fasteners. It seals on the front of the plugs when the fasteners are tightened. The flange on the Wien filter plug will be removed manually when service is required as it is not anticipated that this will occur very often. The ion source plug will be removed remotely. The first step is to de-pressurize hydraulically loaded fasteners that engage between the vacuum flange and the studs that are installed in either the vacuum box or ion source plug. The hydraulic "nuts" are held in a fixture that can be released to a region outside of the flange. At that point, the flange can be moved forward and sideways to remove it from the front of the plug as shown in Figure 9.

Also shown on Figure 9 are two rigid chains manufactured by Serapid. These are both shown out of plain in this figure – they will be oriented vertically so that the return is underneath the source box. The principle of these chains is shown in manufacturer's literature in Figure 11. The chains can push with both strength and precision in one plane as a rigid beam and wrap around inside an appropriately designed storage vessel as a chain in the opposite orientation. This permits long pushing capability without requiring large space behind the pushing point for storage of the device as would be required, for example with a ball screw. A fixture on the end of the chain will engage a mating fixture on the ion source plug and pull it back into the empty source box as shown in Figure 12. The source and box will then be pulled back towards the back of the vault and the chain disengaged. Plates will then be inserted over the front of the box and to hermetically seal the source inside the storage box. The source and its storage box will then be moved to bay on the same level as the vacuum box (see Section 5 for further details). A new source inside a storage box will be installed in the ion source gallery and the process will be reversed.

Figure 13 shows a vertical view of the same region. Four feet of overlapping concrete blocks are used over the main interaction region to reduce both the Bremsstrahlung and neutron fluxes to reasonable levels. This should be adequate to permit rapid access to the main floor of the facility. Rectangular blocks are used over the opposite end of the vault for ease of removal. The source box is supported on two rails above the main vault floor and the chain return is between the two features. It is also proposed to line the vault and the service corridor parallel to it with a stainless steel liner that is as well sealed as practical to help contain accidental releases of fission products and other contamination from the main room above the vault. This will be discussed in more details in Section 6 on Safety Issues.

4.3 Summary

4.4 References

[1] Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Technical Report Series No. **188**, International Atomic Energy Agency, Vienna, 1979, p. 52 and references therein.
[2] Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Technical Report Series No. **188**, International Atomic Energy Agency, Vienna, 1979, p. 176 and references therein.
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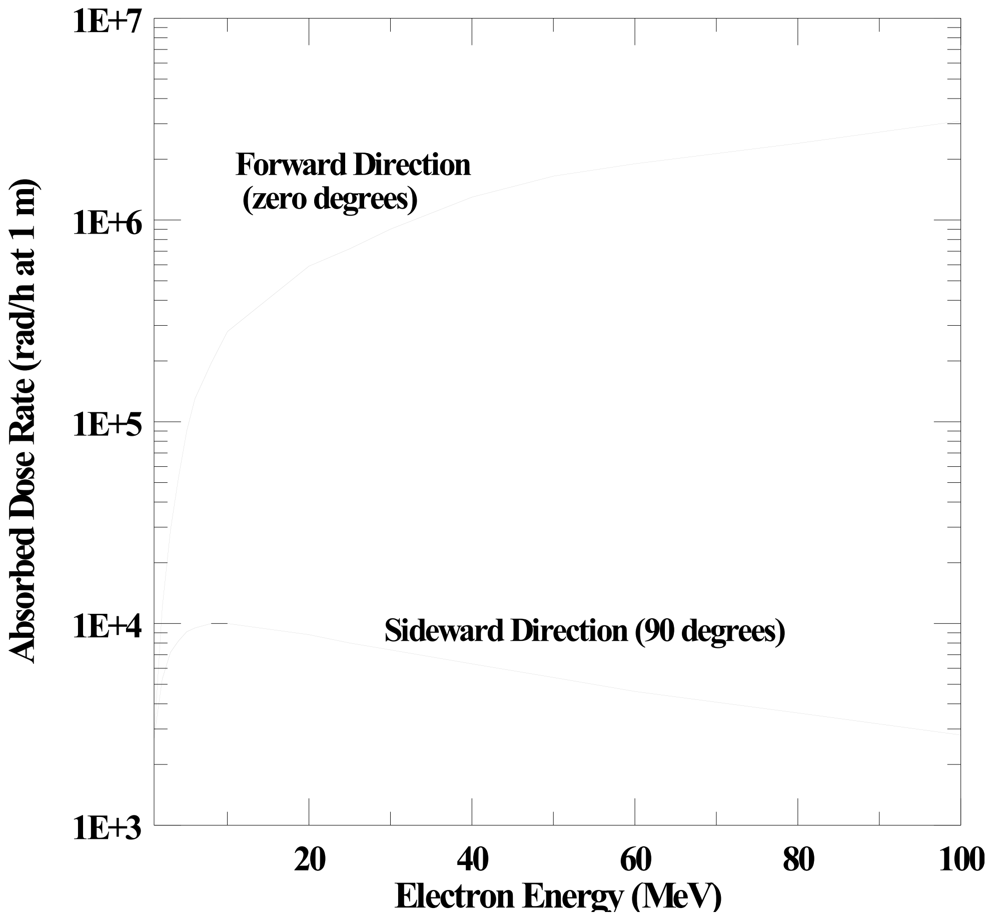


Figure 1. Thick-target Bremsstrahlung yield from a high-Z target [1].

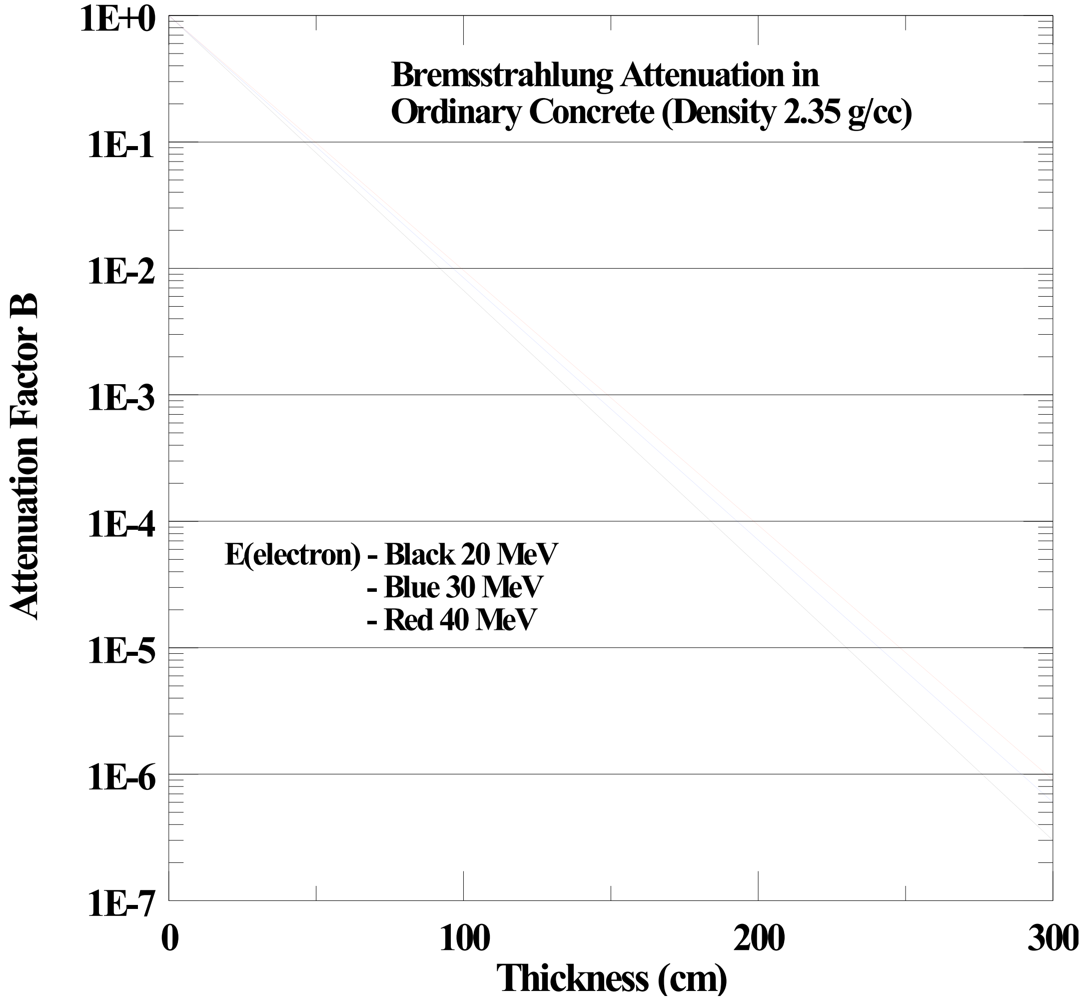


Figure 2. Bremstrahlung attenuation in ordinary concrete for broad beam conditions at 0° to the beam direction [2]. The energy designation refers to the monoenergetic electron energy in MeV.

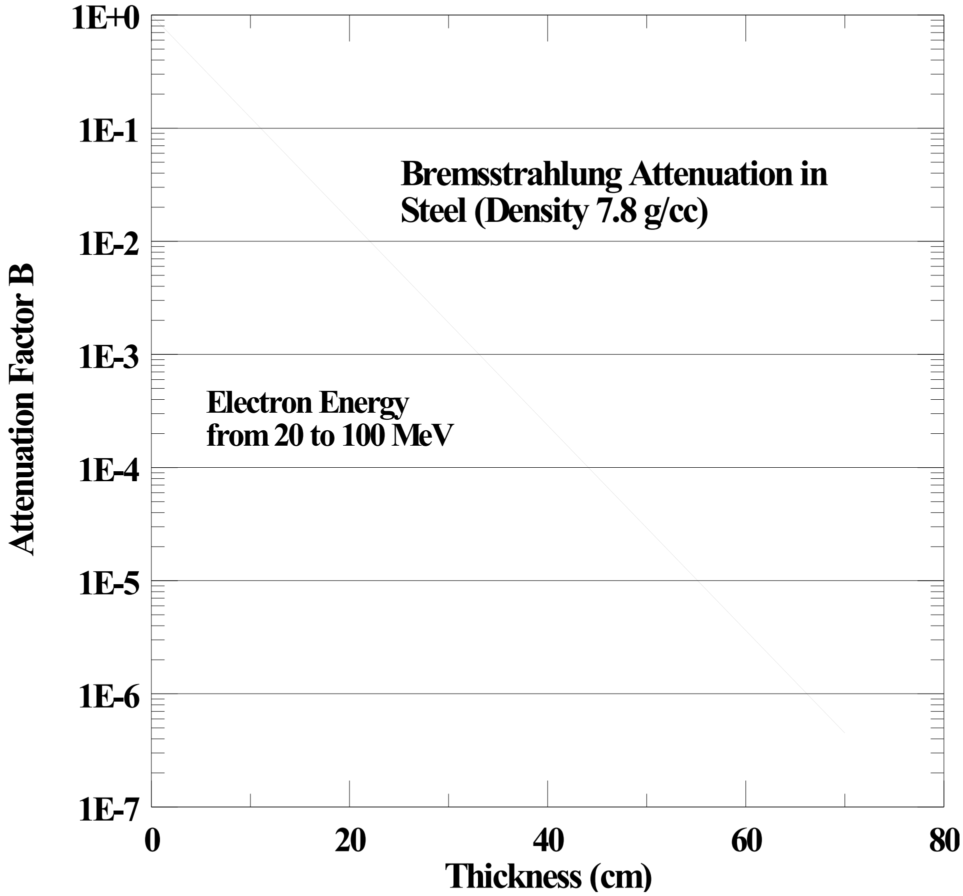


Figure 3. Bremstrahlung attenuation in steel for broad beam conditions at 0^{o} to the beam direction [2]. The attenuation is nearly constant for any energy from 20 to 100 MeV.

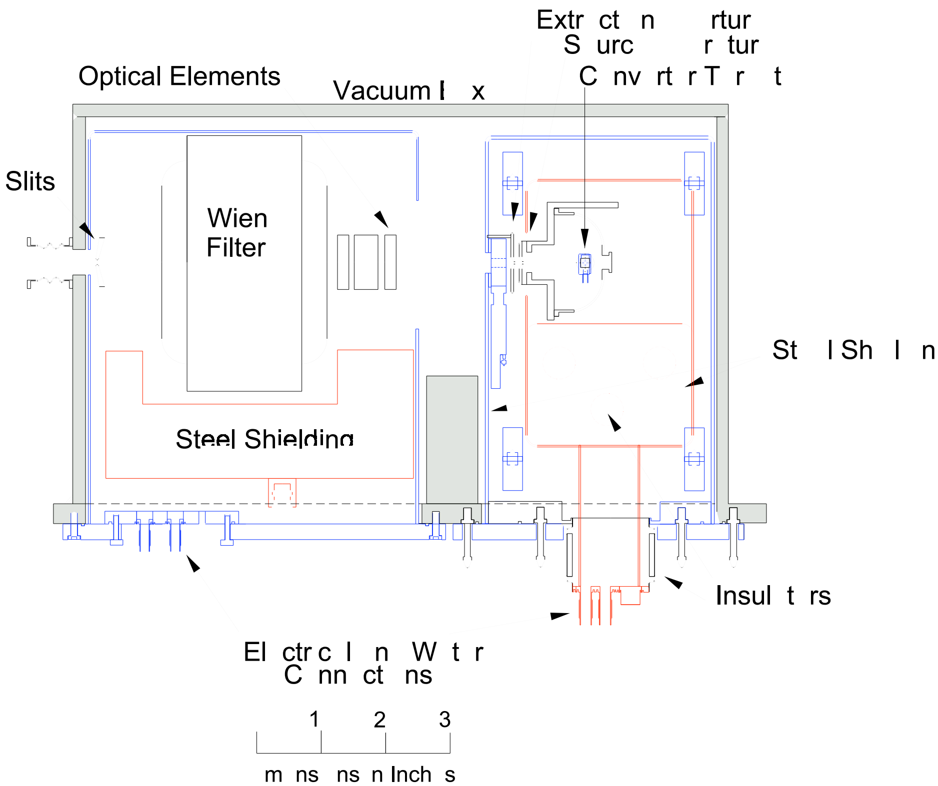


Figure 4. Concept of the target-ion-source plug. The vacuum box is shaded to indicate its extent. Two separate plugs are used. The electron conversion target and the ion source are mounted on one plug and the extraction aperture, optical elements and a Wien filter and slit are mounted on the second plug.

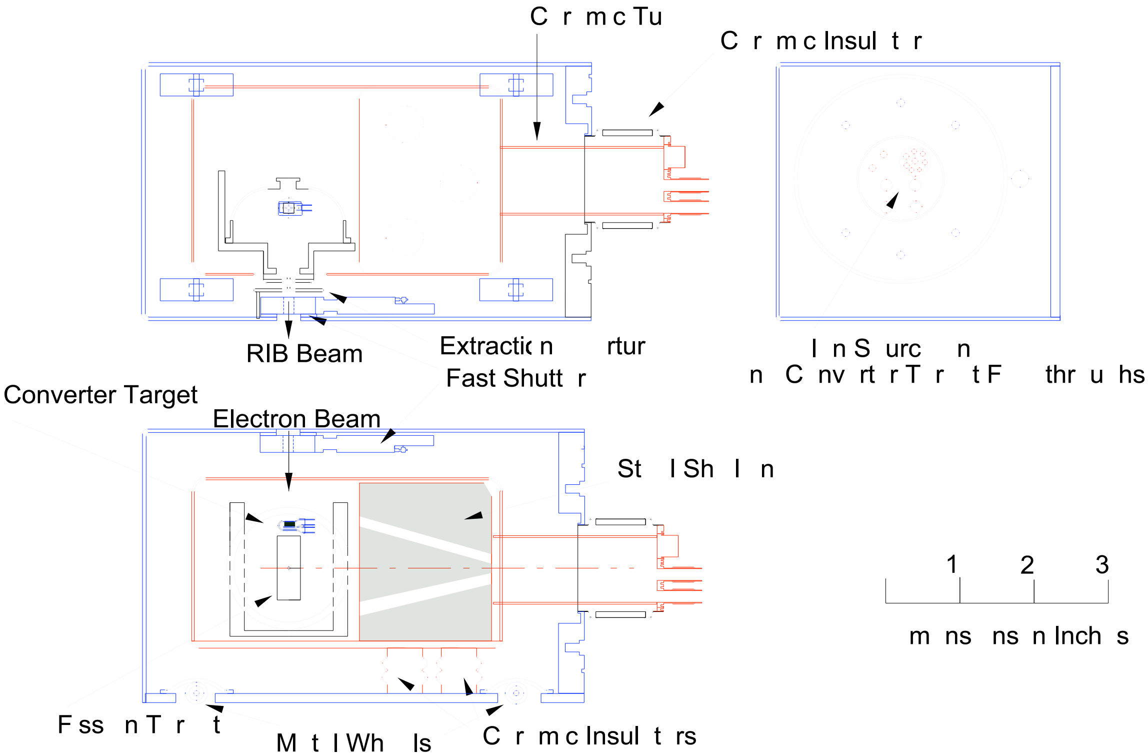


Figure 5. Initial concept of the conversion target and ion source plug.

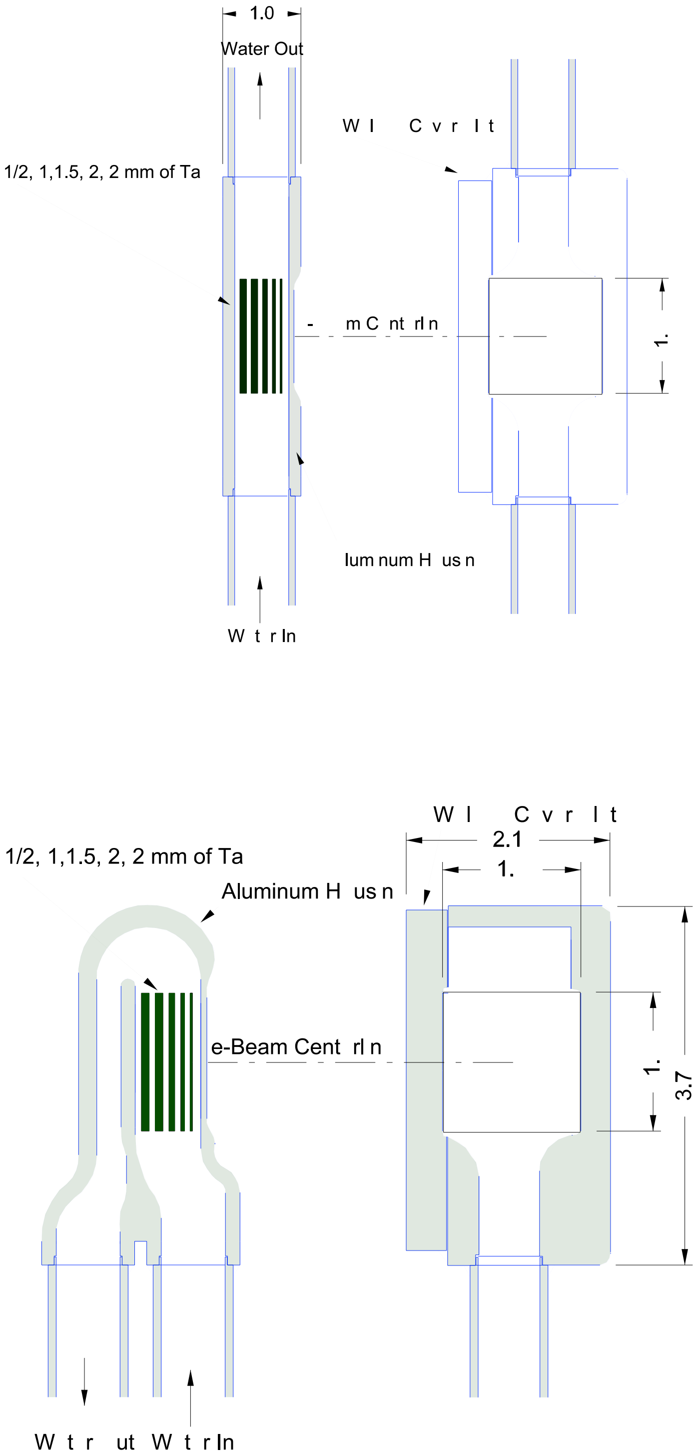


Figure 6. The Bremsstrahlung conversion target. Two options are shown.

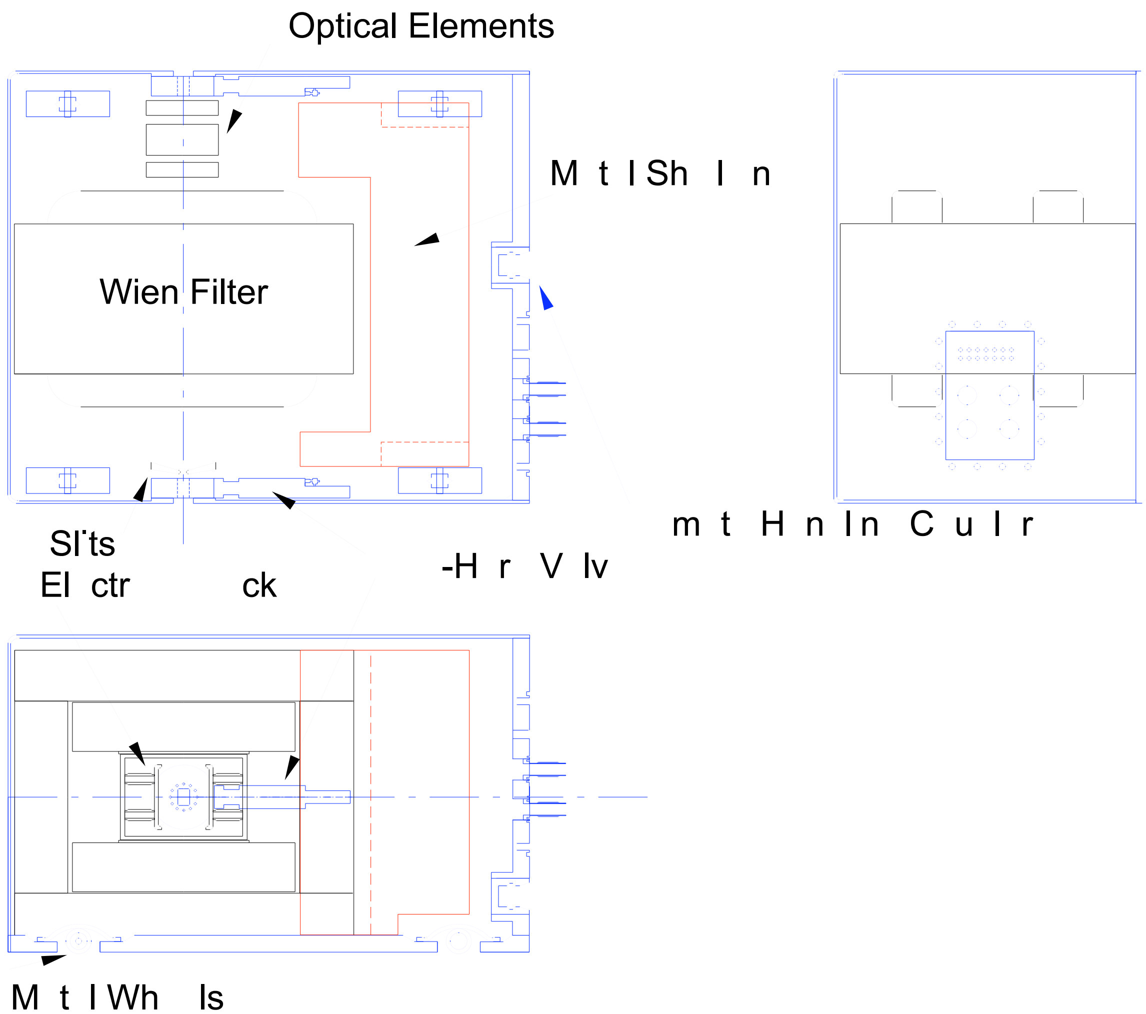


Figure 7. The Wien filter plug, based on concepts developed for the SPIRAL II Project at GANIL [3]. This plug, like the ion source plug, is built on a rigid base with strong metal wheels to permit it to be installed horizontally into the vacuum box. It contains the Wien filter magnet and slits and entrance optical elements.

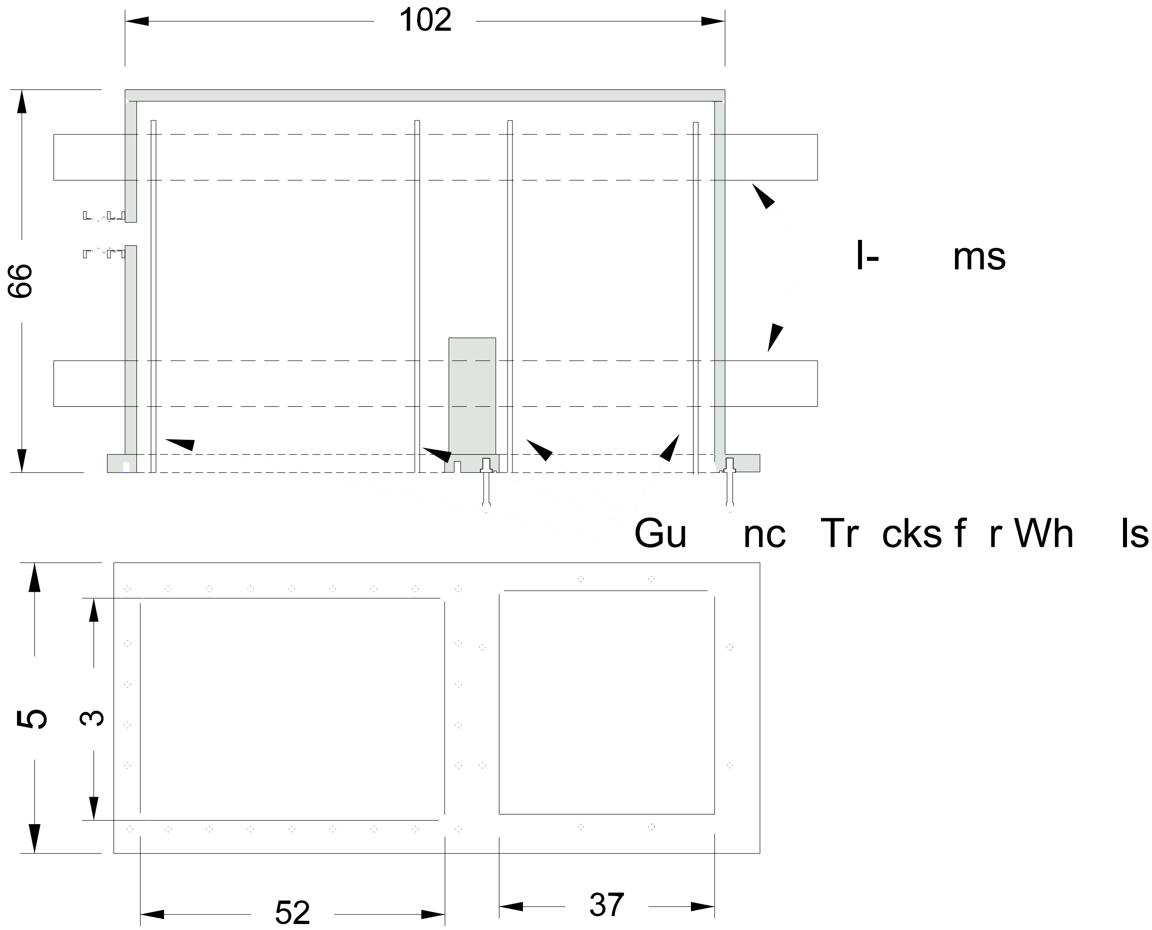


Figure 8. The Vacuum box. This figure shows the basic details of the vacuum box that contains the two plug modules. Tracks will be machined into the base of both sides to guide the plugs into their final position.

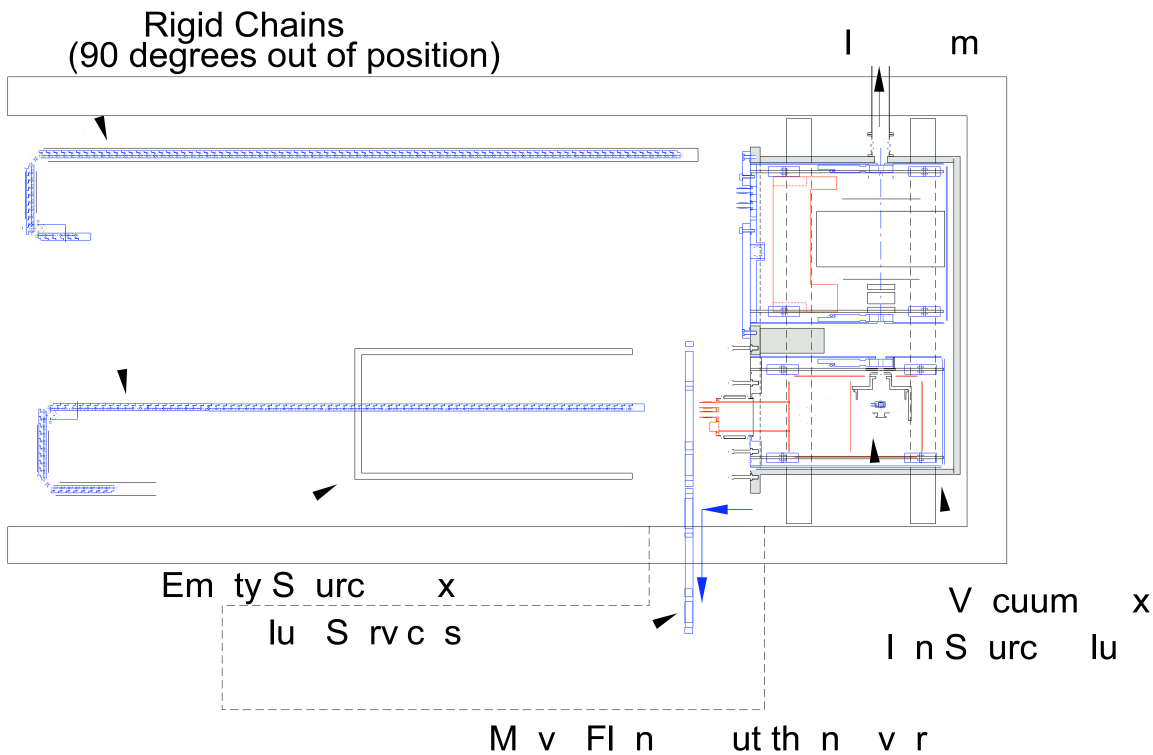


Figure 9. Initial concept of ion-source plug handling.

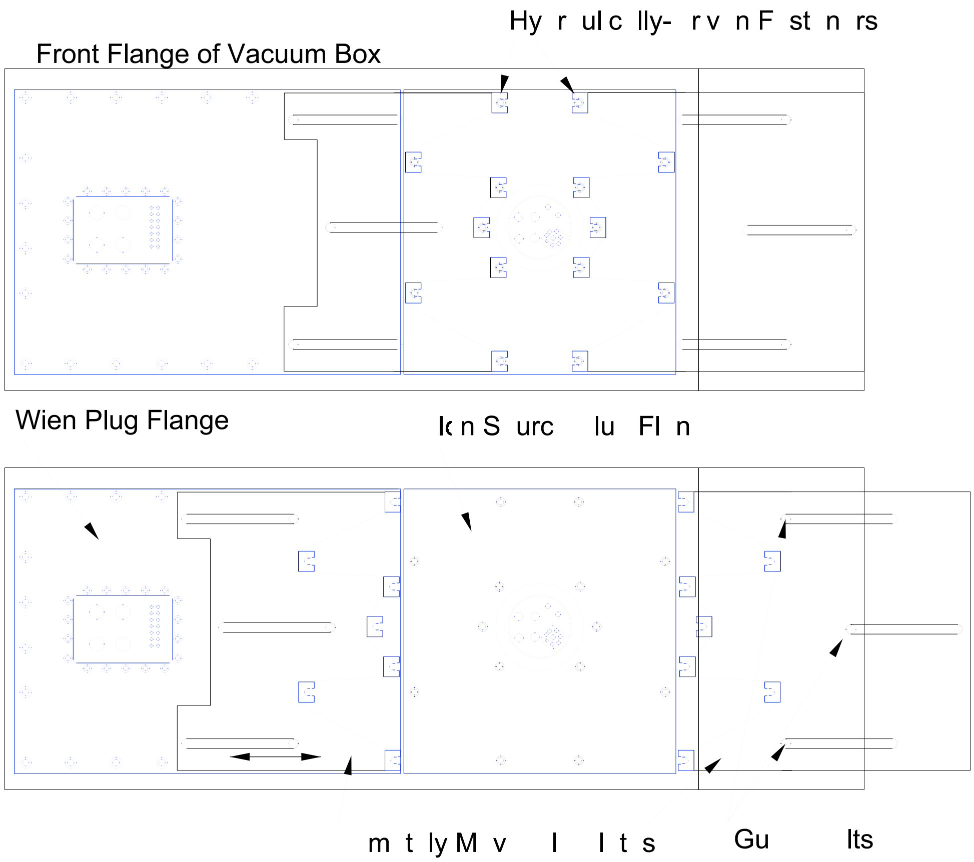
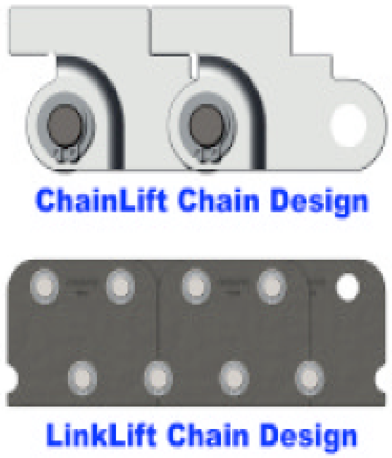


Figure 10. Remote removal of the ion-source-plug vacuum flange.



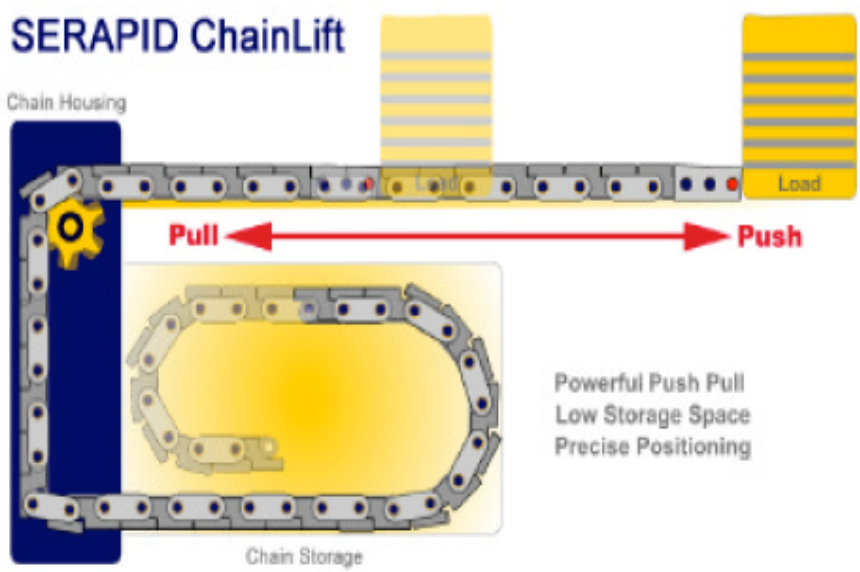


Figure 11. Principle of the Serapid rigid chain. The chain pushes as a rigid beam in one orientation and wraps around inside an appropriately designed storage vessel as a chain in the opposite orientation. This permits long pushing capability without requiring large space behind the pushing point for storage of the device as would be required, for example with a ball screw.

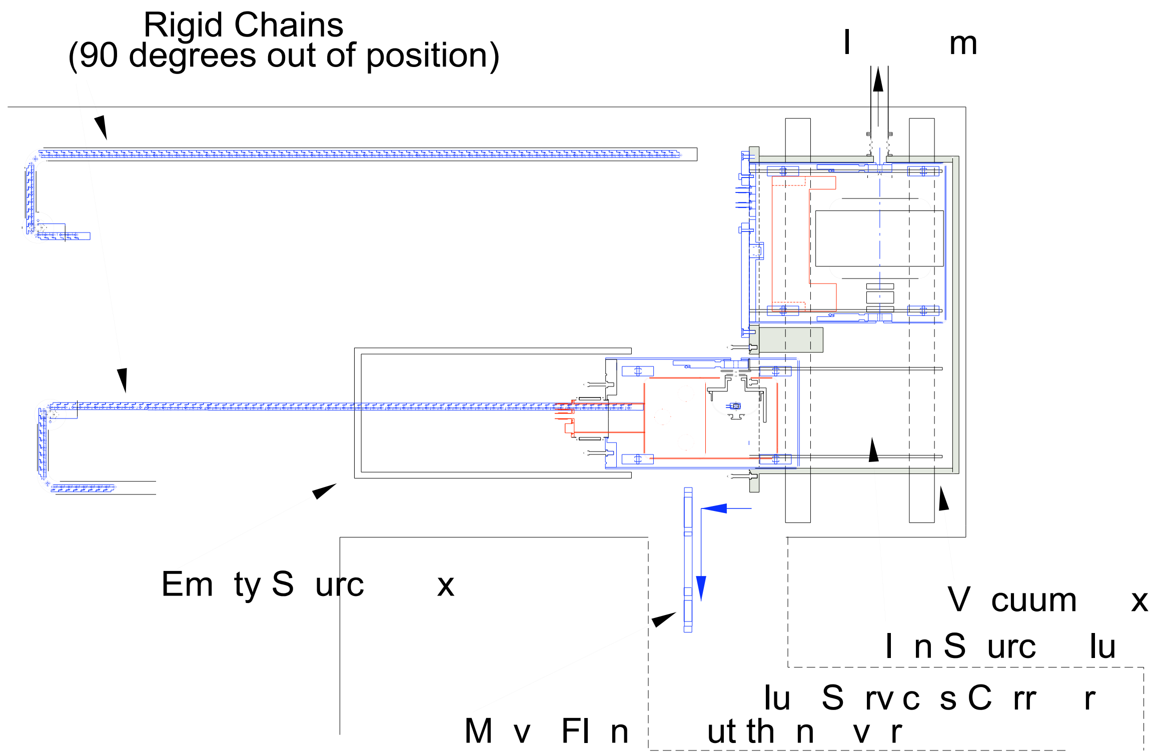


Figure 12. Second stage of ion source removal. The vacuum flange has been moved aside and the rigid chain has started to pull the ion source into a storage box. The other chain is used to remove the beam selection plug.

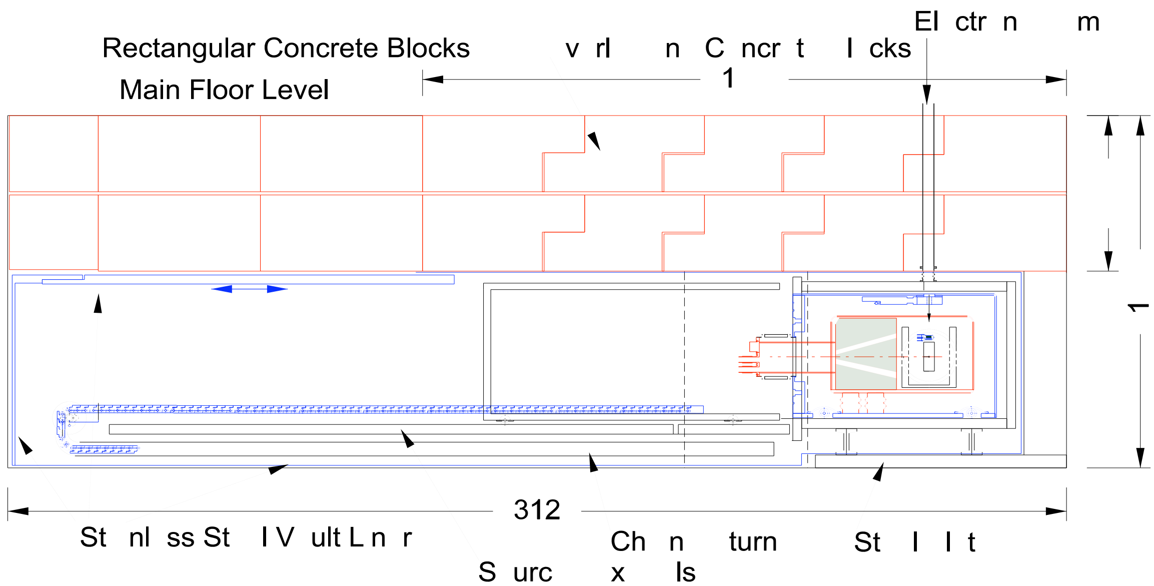


Figure 13. Vertical view of the ion source vault.

5.0 Facility Layout

Figure 1 shows the general layout of the lower level of the Holifield Radioactive Ion Beam Facility with items presently under construction as part of the IRIS2 project shown in red. RIB beams from the new facility will need to be transported from the new facility to the isotope separator before injection into the Tandem accelerator. Initial ideas for an appropriate site for the new facility are based upon locations that could permit a beam transport line from the driver facility to the isotope separator with minimal disruption to existing facility components and other concerns such as blocking access to shipping doors. It will not be possible to use the RIB source on a high voltage deck as has been done for the other RIB sources in use in the facility. Transport studies will be done to determine if the RIB beams should be accelerated to about 250 keV using a Radio Frequency Quadrupole (RFQ) accelerator either before or after the isotope separator or inject the 30 to 40 kV beam directly into the Tandem. The conclusions of these studies may also impact site location decisions.

Based upon the initial considerations, a starting point for the new facility is noted on Figure 1, just outside of the wall of the Isobar Separator and the Tandem. There is not a lot of space available and several existing features outside of the facility walls will need to be relocated including a length of water main buried under that area and also the large cooling tower. There is an independent effort to replace the almost-50-year-old cooling tower with a new tower in a different location to permit facility operation until the transition occurs. This would remove the location of the cooling tower as a significant concern in the decision to locate the driver facility.

Figure 2 shows the proposed Rhodotron-based electron driver facility in the context of the existing HRIBF, and Figures 3 and 4 provide a more detailed look at the upper and lower level levels, respectively. In this arrangement, a new building would be constructed to the south of the existing facility, leaving space for a possible future new experiment hall. The new building would connect to the existing facility by a new RIB transport corridor.

The upper level (Figure 3) shielding around the Rhodotrons is 6 feet of standard density concrete as recommended by IBA. A removable steel shielding plug in the ceiling will provide a means of installing the accelerators in the room, and a 5-ton hoist will be used to lift the top half of the machines for maintenance. To the south of the Rhodotron room, an unshielded utilities room will be constructed to house power supplies, controls, cooling systems, and chiller. Personnel will access the Rhodotrons through a labyrinth that is accessed from within the utilities room.

The lower level (Figure 4) is heavily shielded around the RIB target plug and the plug handling and storage system. Walls nominally consist of 9 feet of standard density concrete. Excavation is required to locate the building directly on bedrock at approximately 7 feet below grade. Both concrete and steel shielding will be utilized around the plug area, and wall thicknesses may ultimately be reduced by using a combination of these materials. A hot cell would be located below the utilities room, providing a location for disassembly of activated target ion source plugs after an appropriate cooling period. Two remote manipulators will be used to remove plug components and place them in storage containers for disposal. A small shielded corridor is included to provide access to these storage containers, and also to bring new source plugs into the facility for installation. Enough storage space has been included to house multiple new and used sources.

Figure 5 shows an elevation view of the facility looking west. Beam from the second-stage Rhodotron is directed downward by means of the 270 degree bending magnet, and a long-lever-arm scan horn would be located below the magnet in the Rhodotron room to raster the beam in two dimensions across a target. Radioactive ion beam would be extracted to the north at approximately grade level and then elevated by electrostatic components in the RIB transport corridor to the elevation of the isobar separator beamline. This elevation scheme also provides a ready means of implementing a laser system for beam purification.

Similar layouts will be developed for the superconducting linac option. The building location, shielding requirements, and two story arrangement would be quite similar to the Rhodotron-based facility.

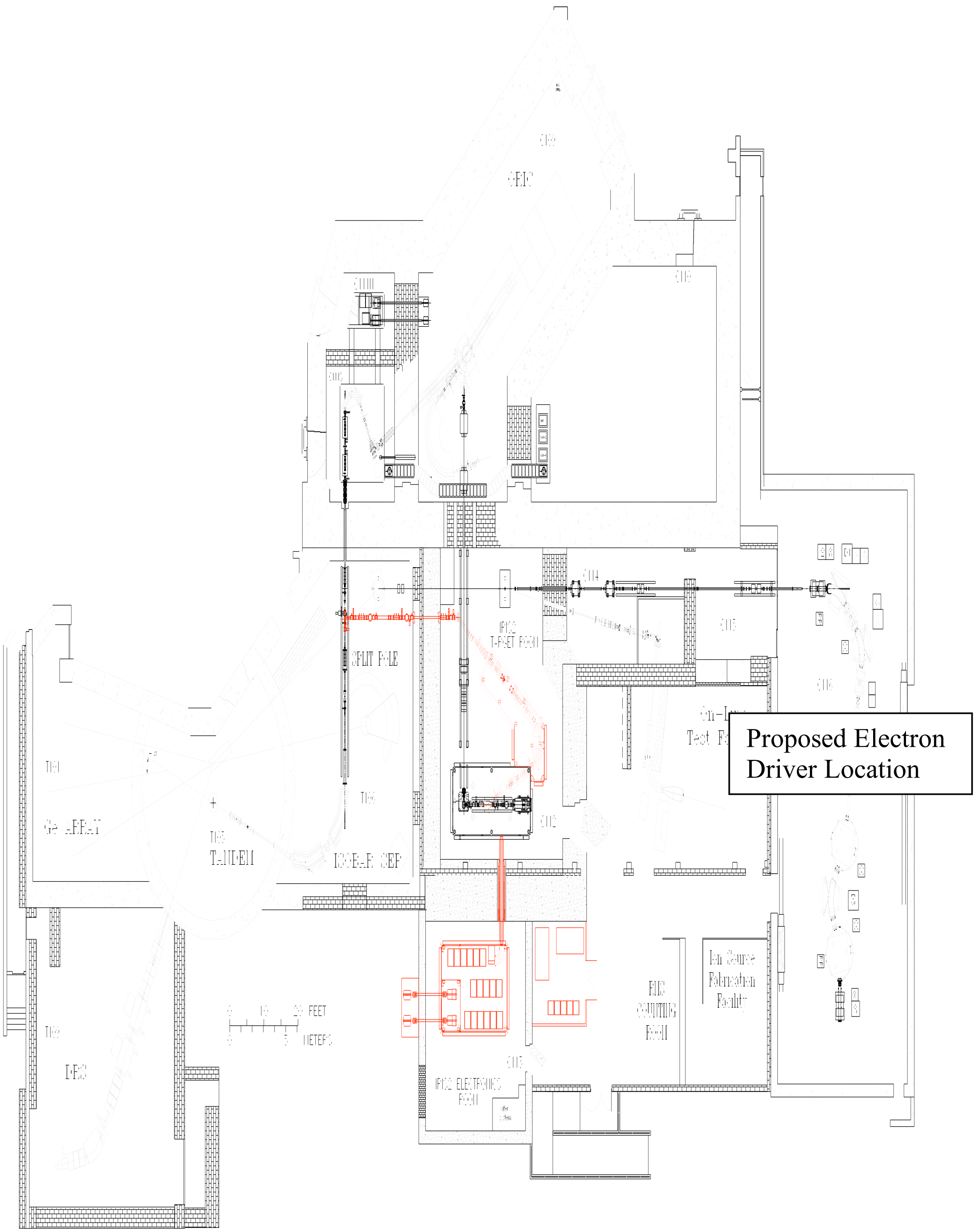


Figure 1. Plan view of the existing HRIBF with components currently under construction as part of the IRIS2 project shown in red.

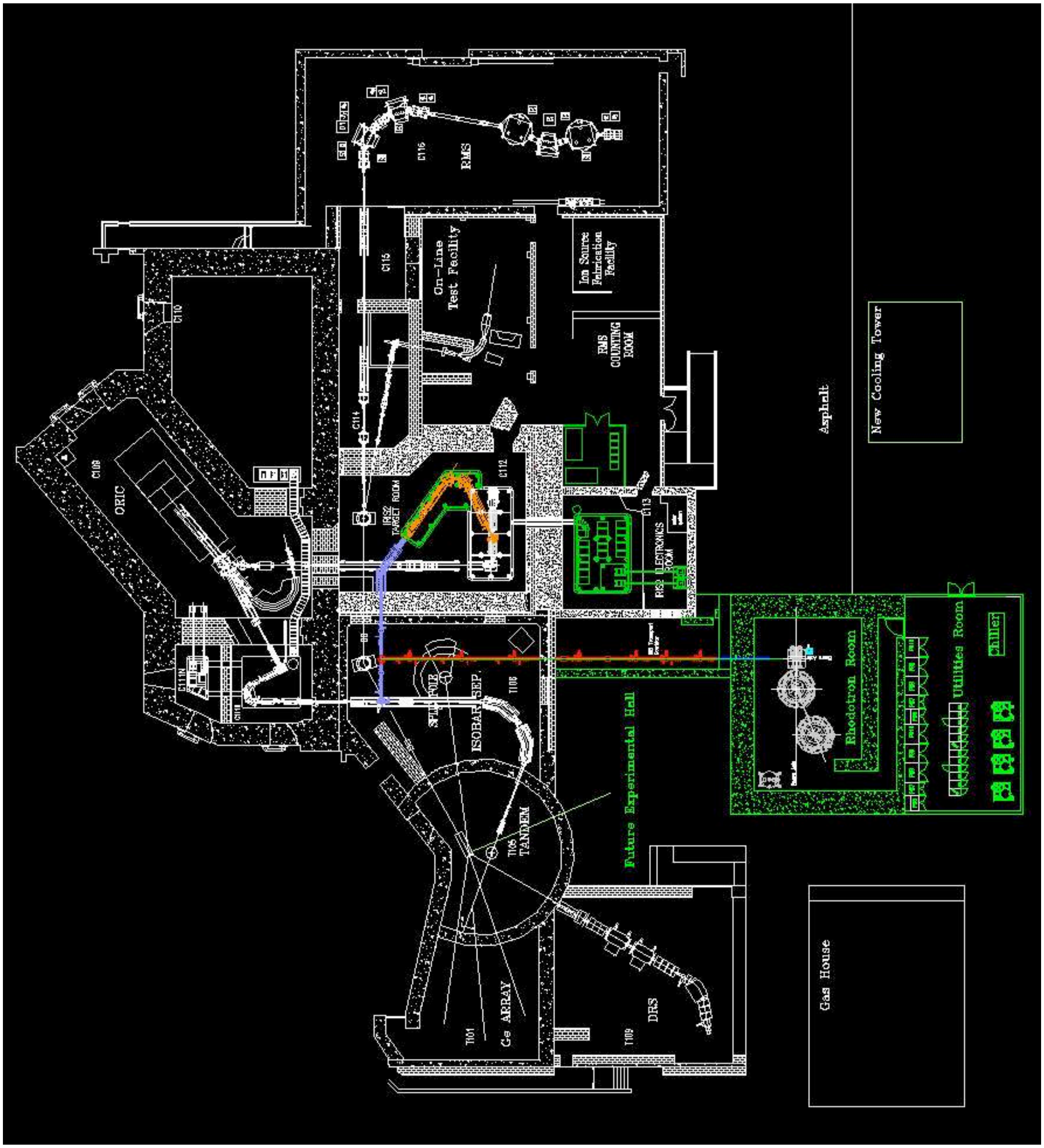


Figure 2. Potential layout of an electron driver facility using two Rhodotron accelerators.

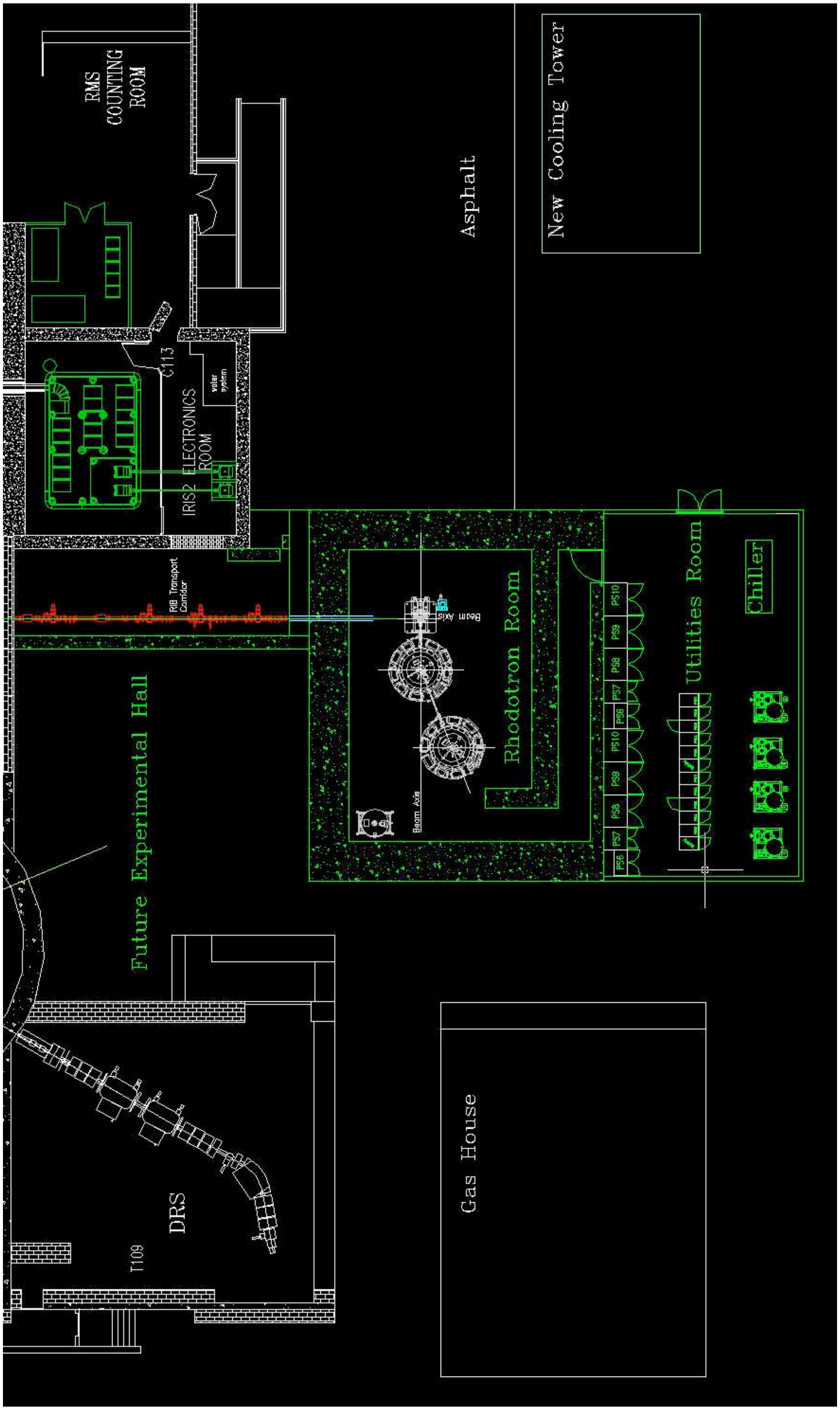


Figure 3. Facility layout plan view at the upper, Rhodotron, level.

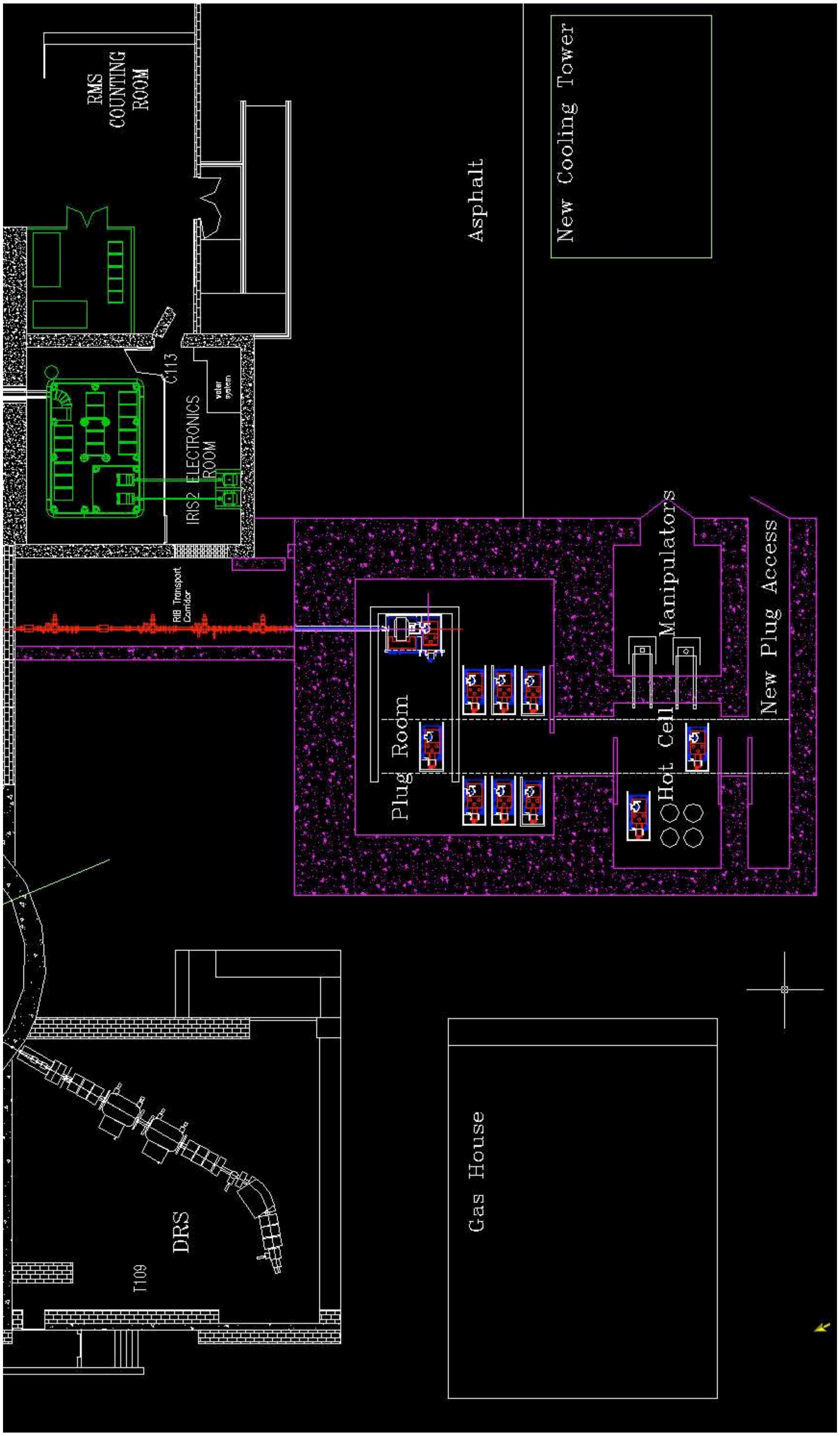


Figure 4. Facility layout plan view at the lower, source plug, level.

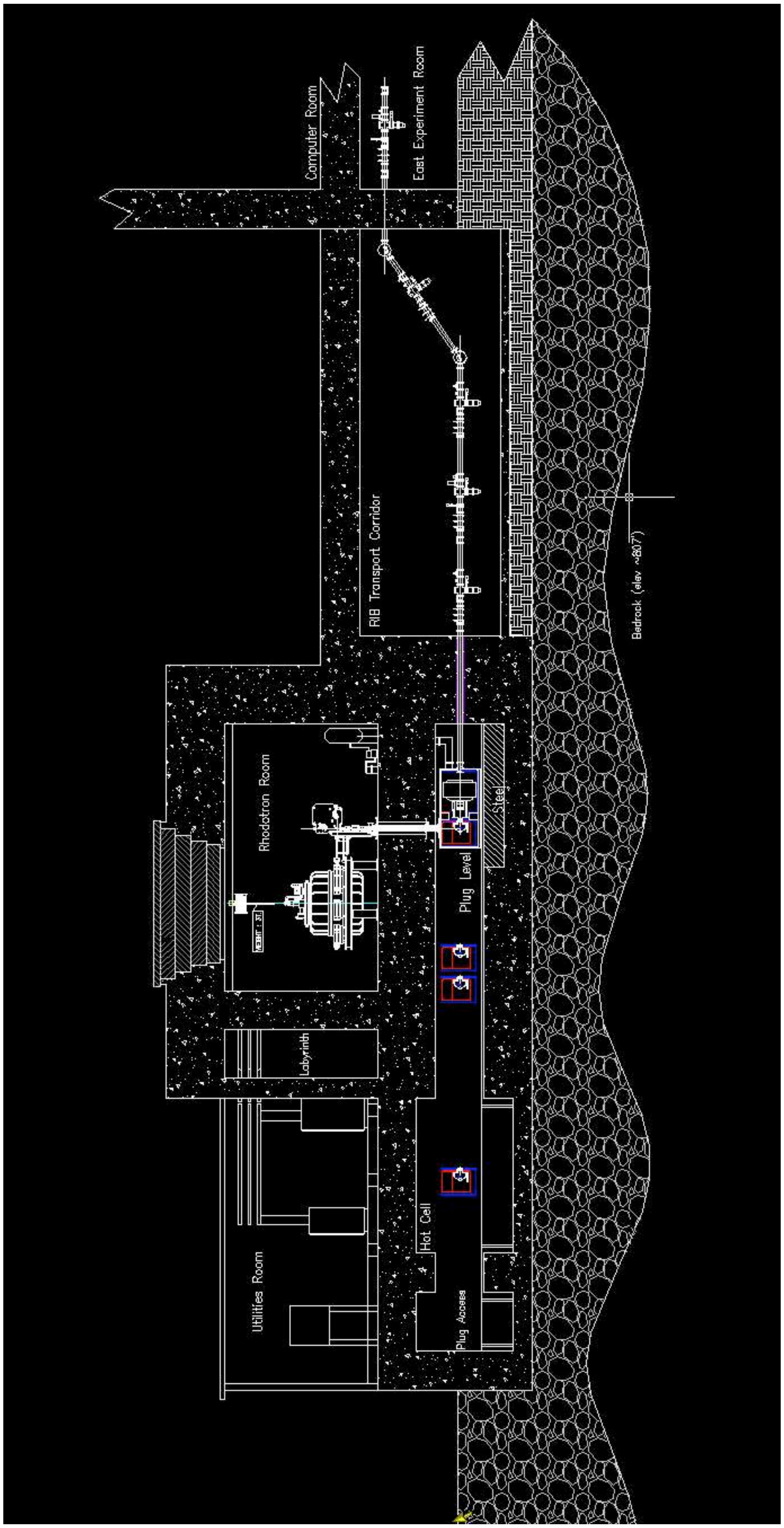


Figure 5. Facility layout elevation view looking west.

Section 6. Radiation and Facility Safety Concerns

6.1 Introduction

A high-power electron linac has the potential to produce very high radiation fields from Bremsstrahlung photons and photoneutrons. This will occur wherever the electrons interact, whether intentionally at the converter target or any place that a small fraction of beam is lost during transit to the interaction region. The facility must be shielded to protect any occupant outside the walls from radiation exposure outside of the limits for the various posted zones during routine operation and there must be a safety system in place to rapidly shut the electron beam off during excursions outside of normal operation parameters. The shielding also needs to be designed to prevent a serious radiation exposure during the short response time to an excursion. Beyond the radiation fields produced during operation, there is substantial activation of the converter target and fission target and all of the components of the two plugs. The fission target contains the many activities of fission including gaseous isotopes of Krypton and Xenon. Systems must be in place to contain these activities. During operations such as target plug replacement there is also the possibility of spreading radioactive contamination. Because of the intensity of the forward-directed Bremsstrahlung beam, the facility shielding must be adequate to prevent possible ground-water contamination, especially if the beam is directed vertically into the earth below the facility floor.

6.2 Facility Shielding

The initial point in facility shielding is the reduction of the intense Bremsstrahlung beam to safe levels. Figure 1 shows the thick-target Bremsstrahlung yield per kW of beam power at zero and 90^{o} with respect to the electron beam direction from a high-Z target. The dose rate in the forward direction for 25 MeV electrons is about 7×10^{5} rad/h at 1 m. For a nominal 70 kW beam power the rate is about 5×10^{7} R/h at 1 m. If the requirements were to reduce this to levels suitable to general occupancy at 1 mR/h, more than 4 m of concrete (see Figure 2) plus the $1/r^{2}$ reduction provided by the shielding length would be required. Figure 2 also contains an approximate indication of the attenuation of the Bremsstrahlung at 90^{o} by concrete shielding. The spectrum at 90^{o} is fairly close to the forward spectrum from a 10 MeV electron [1]. One other thing to note from Figure 2 is that the amount of shielding required to reduce the Bremsstrahlung radiation to safe levels is more than needed to reduce the photo and fission neutrons to safe levels. Therefore, the focus of overall facility shielding is on the Bremstrahlung sources.

Figure 4 shows a layout of the main floor of the electron driver in the preferred location. Noted on this figure are distances (in inches) to other parts of the Holifield facility in adjacent rooms. Both the Rhodotron accelerators and especially a superconducting linac are designed to operate with minimal beam losses. If the assumption is made that the maximum long-term loss that can be tolerated is less than one percent at full electron energy, then several possible sources can be defined. The most likely location is where the 25 MeV electron beam bends through 270^{o} before transportation vertically to the converter target below the floor. The penetrating forward directed Bremsstrahlung cone will be toward the back wall or roof as the electron beam passes through the magnet. The shielding shown plus the distances between potential source terms and occupied areas is adequate for a continuous loss term of one percent. Given the intense power in the beam, accidental loss of the entire beam would rapidly lead to any component on this level being damaged sufficiently that the vacuum would degrade preventing any further operation. This would occur within seconds. The radiation fields in potentially occupied zones could be temporarily beyond posted limits but the integral of dose times time before either shutdown or component failure would remain well inside of acceptable limits for a radiation worker. There will also be ion chamber radiation detectors distributed throughout the facility to monitor radiation levels and provide a signal for fast shutdown during any excursion. The safety interlock system and exterior doors will prevent any occupancy in the main accelerator room during any operations. The interaction region has substantial extra shielding, especially between the source and any line-of-sight to potentially occupied zones. The facility, as laid out conceptually in Figure 4, should have adequate shielding for routine operation and upset conditions resulting from component failure.

Because the electron accelerators are designed to have low beam loss during normal operation, there will be little activation of the beam lines, and only after the exit of the second Rhodotron once the electrons have reached higher energy. Personnel should be able to enter the floor almost immediately after shutdown of the beam.

6.3 Target Plug Shielding

6.3.1 Shielding From Bremsstrahlung

The area including the target vault and the target plugs are the areas of the most critical concentrations of radioactive materials and potential for contamination. The very high intensity of Bremsstrahlung is also produced at the conversion target. A number of special considerations are applied to manage this region of the facility. The intense Bremsstrahlung is managed by directing the forward cone vertically into the facility. Four feet of concrete shielding is used above the target plug to contain the neutrons so that there is not significant neutron activation on the main floor. This extra shielding, in combination with the rest of the facility shielding, is sufficient to protect anyone in an occupied area outside the facility walls.

6.3.2 Ground Water Activation

There is concern of possible ground water activation from the intense forward cone of Bremsstrahlung and accompanying photoneutrons. One initial thought on this is to use about two feet of steel directly below the target plug, and one foot of steel on three sides of the vacuum box followed by another meter of normal density concrete to absorb the neutrons. Figure 4 shows the attenuation factor of steel for bremsstrahlung produced by electron energies from about 20 to 100 MeV. The attenuation factor will be higher for angles not in the forward cone. This combination shield will reduce the radiation fields outside the shield to very low amounts and prevent any activation of ground water. The total amount of steel will not be excessive because it can be placed quite near the source.

6.3.4 Fission Products and Other Plug Activation

Figure 5, from the GANIL study of the electron beam option for SPIRAL II, shows the calculated buildup of fission products in a fission target operating at 10^{13} fissions/second for 15 days and a second curve on the same x - axis shows the decay after the conclusion of the run. This facility is designed to provide the same level of irradiation of the target and this calculation should hold for it. The level reached is about 1500 Ci after 15 days of running and decay to about 20 Ci a month after shutdown. For runs approaching 6 weeks, the level may rise to as high as 2000 Ci. Most of the decays will be a beta decay followed by several gamma rays of total energy in excess of 1 MeV. A conservative rule-of-thumb for the radiation level from a gamma-ray source is that a one Ci source produces one rad/h at 1m from an unshielded source. Therefore, it will not be possible to handle these plugs with hands-on work for some time after the termination of the irradiation. The steel shielding between the interaction region and the front of the plug will shield that area from the radiation source and permit access there if required. However, all of the other sides will not be shielded significantly. The main purpose of the front-side shielding is to reduce the Bremsstrahlung sufficiently to permit the use of O-ring seals and rubber or plastic-coated cables and hydraulic lines for connections of services. Figure 6 shows the approximate levels and decay of the main gaseous fission products after an irradiation of 15 days at 10^{13} fissions/second. In a period of one month, the strongest isotope has decayed to less than $1/10^{th}$ curie. The ion source plugs will be stored in hermetically sealed containers for long as practical to permit the gaseous fission products to decay. Most of the gaseous fission fragments will not remain with the fission target during routine operation. They will be ionized and extracted as ion beams. Following the same approach proposed by GANIL [2], the exhaust of the vacuum pumps will be stored in one of several evacuated tanks for 30 to 60 days to permit the gaseous fission fragments to decay to reasonable levels before controlled release.

It is also proposed to handle the target plug remotely once new or refurbished plugs are installed at the vault level of the facility. They will be transferred to the storage area in front of the Wien Filter plug. The ion source plug will be removed, placed in its hermetically sealed box and transferred to one of the storage spaces (Figure 3, Section 5). The new source plug will then be installed and the services re-connect.

It is proposed to maintain the lower vault area as isolated from the main floor as can be reasonably achieved. The air handling system of the lower vault space would be handled through a series of HEPA filters and adsorption columns to reduce spread of radioactive gases and contamination. The floors and walls should be sealed or covered with a layer of thin stainless steel to help in any cleanup of contamination if it should occur. It is proposed to work on the safety aspects of this facility from the earliest stages of design to ensure that safe operation of the facility is the highest priority in the design.

6.4 References

[1] NCRP Report # 144, Radiation Protection for Particle Accelerator Facilities, (Dec. 2003) p.167.
[2] SPIRAL II Project (Electron Option), Preliminary Design Study, GANIL/SP12/007-A.

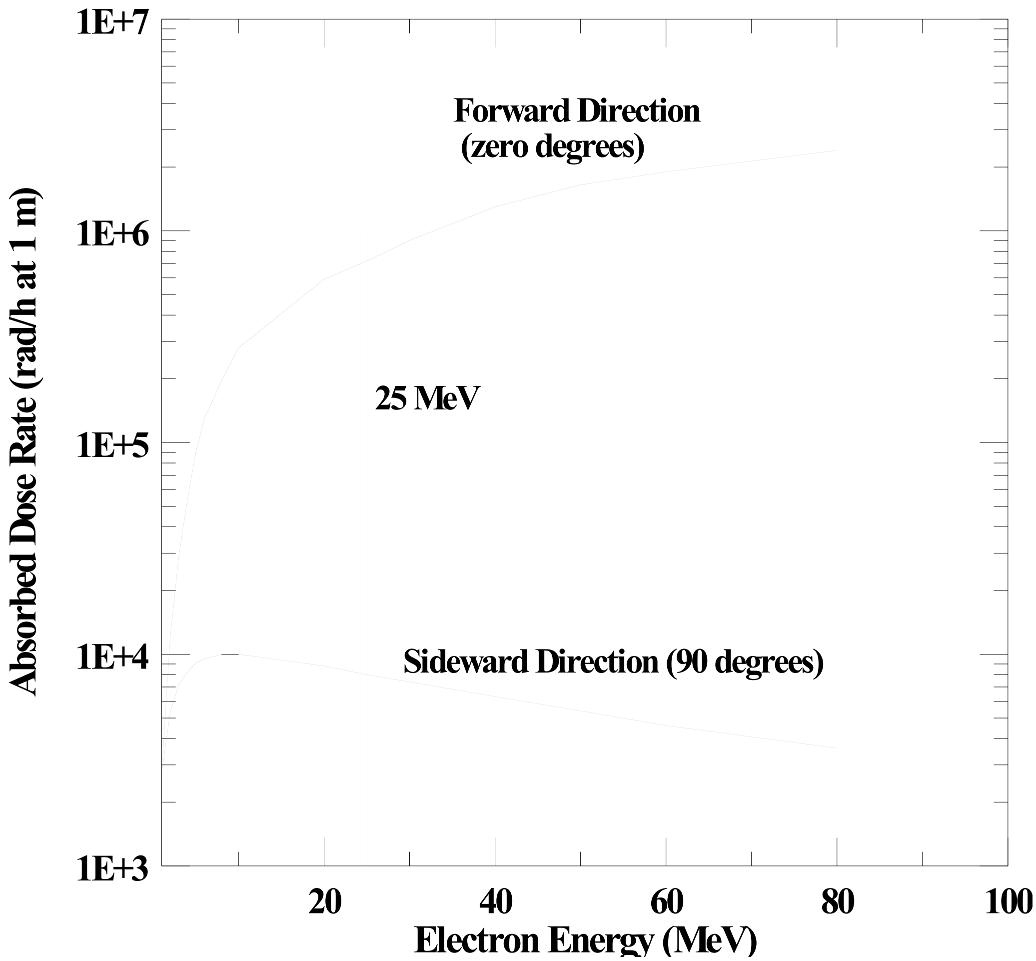


Figure 1. Thick-target Bremsstrahlung yield per kW of beam power at zero and 90^o with respect to the electron beam direction from a high-Z target.

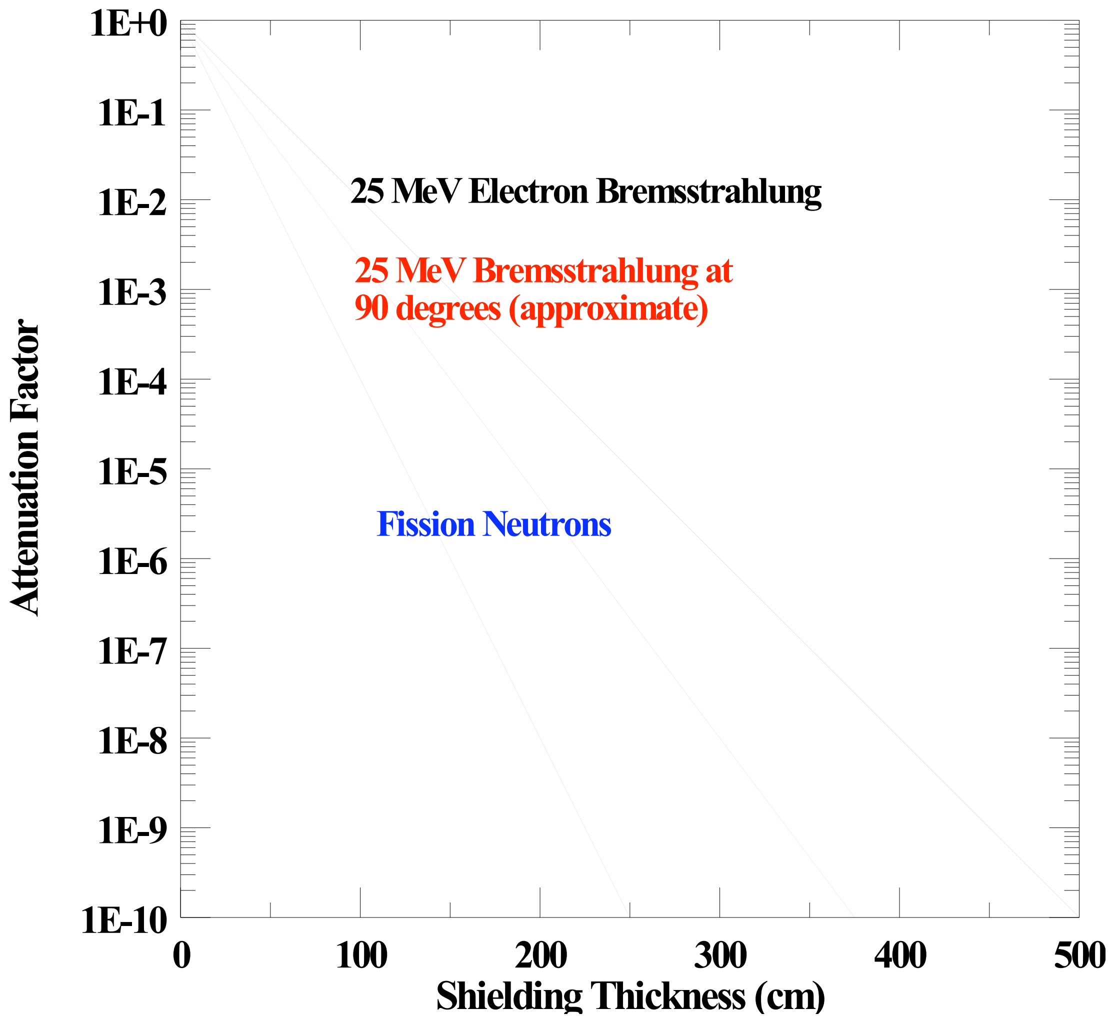


Figure 2. The attenuation factor in normal density concrete of Bremsstrahlung produced by 25 MeV electrons. The red line shows the attenuation of 10 MeV electrons that have a fairly close spectral match to 25 MeV electron Bremsstrahlung at 90^{o} [1]. The attenuation of the high-energy component of fission neutrons in concrete is also shown.

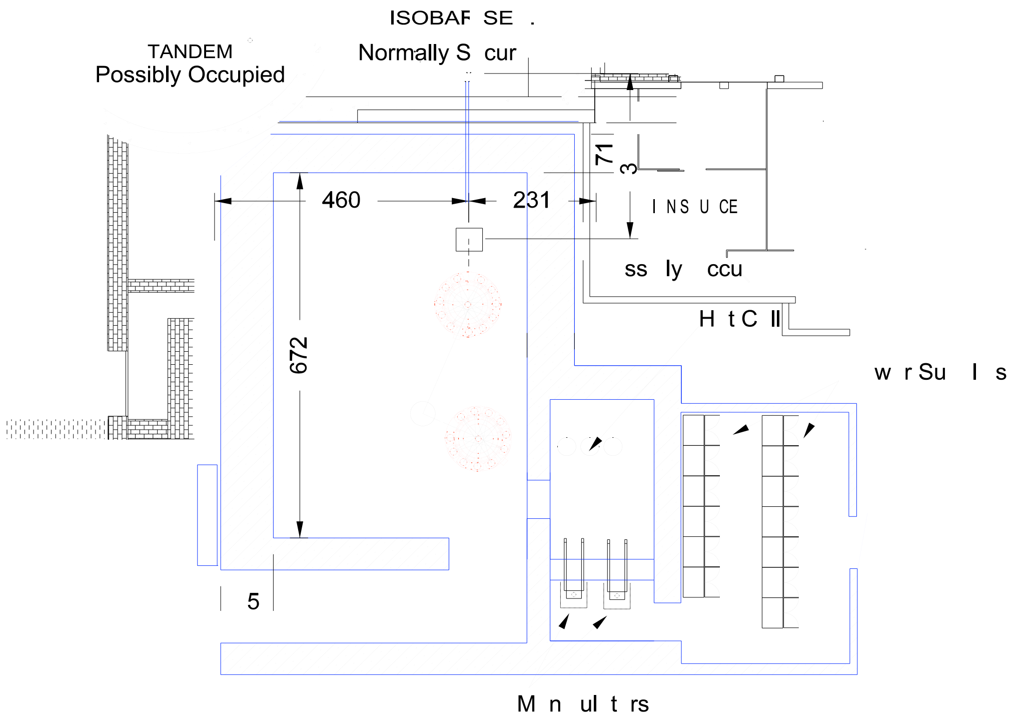


Figure 3. Main floor of the electron driver facility. Some dimensions (in inches) are noted between the most likely source of radiation on the main level and closest locations in the Holifield facility.

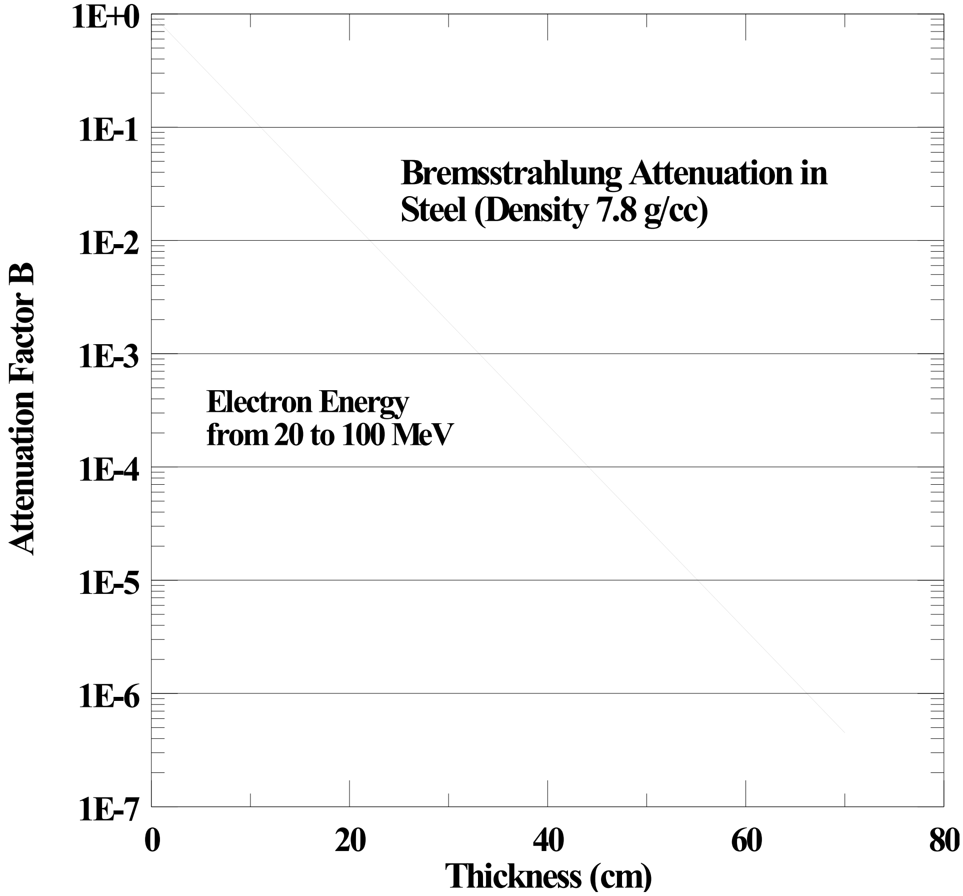


Figure 4. Attenuation factor for Bremsstrahlung in steel shielding.

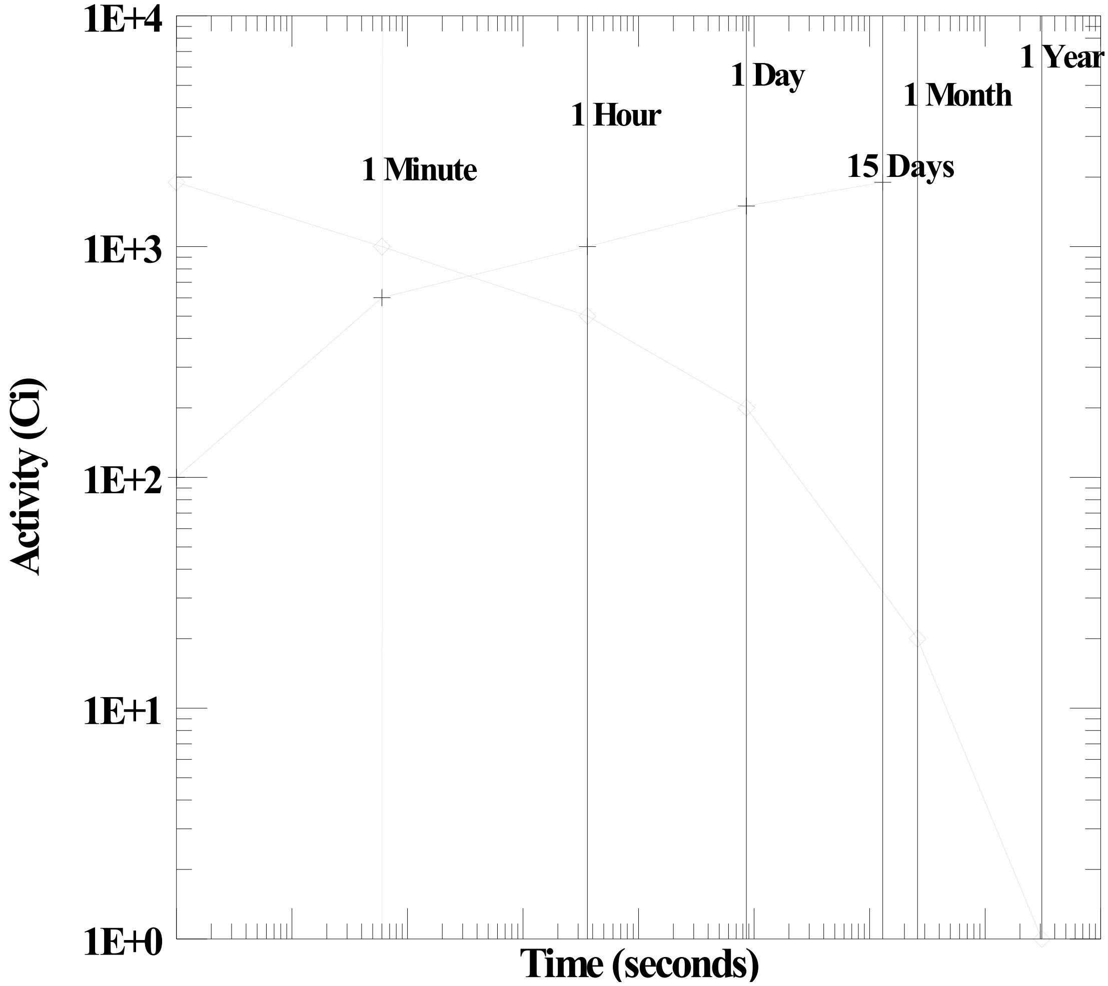
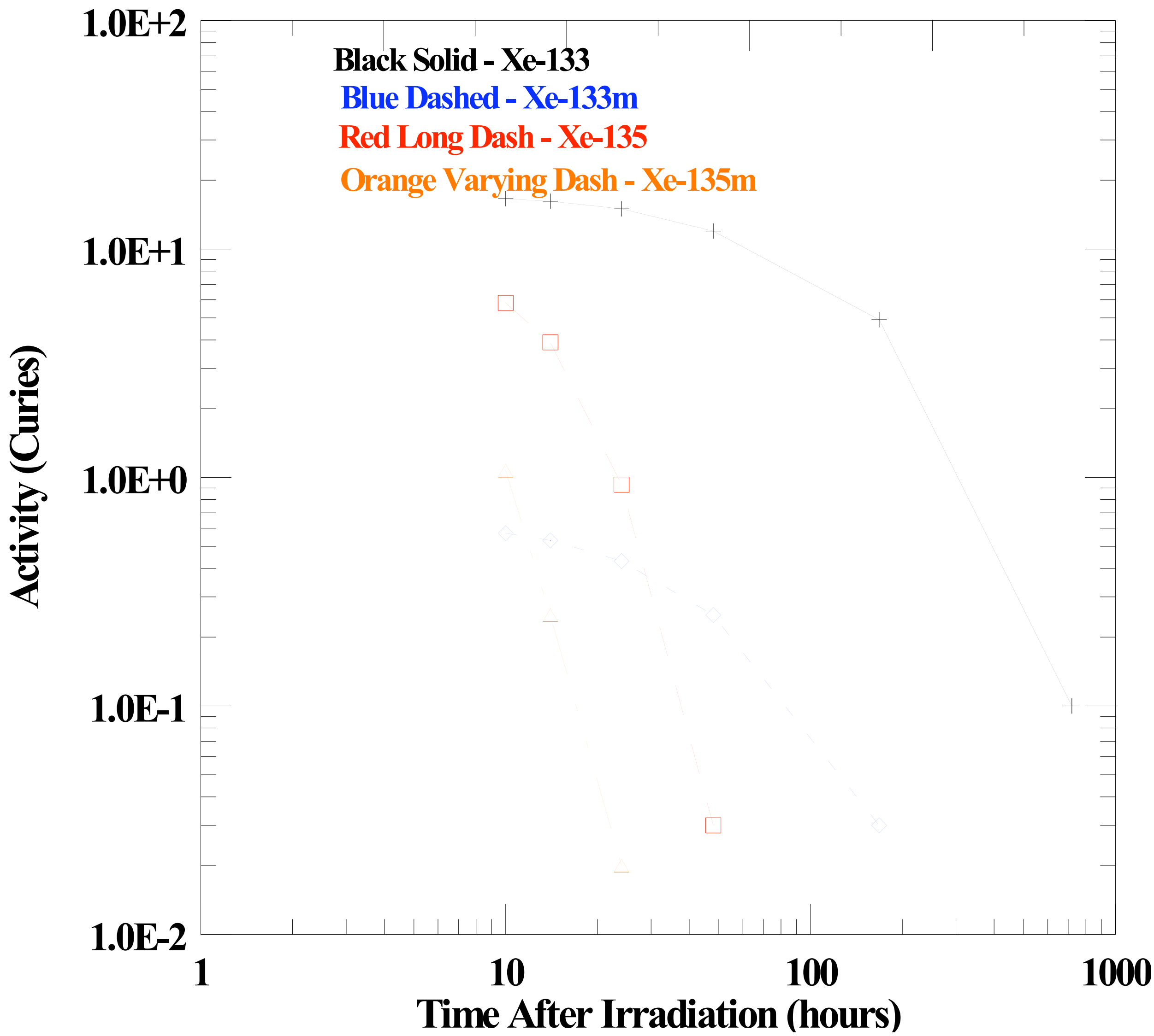


Figure 5. Buildup and decay of fission products in the fission target. Assumed continuous operation at 10^{13} fission/second for 15 days.



1.0E+2
1.0E+1
1.0E+0
1.0E-1
1.0E-2
Activity (Curies)
1
10
100
1000
Time After Irradiation (hours)
Black Solid - Xe-133
Blue Dashed - Xe-133m
Red Long Dash - Xe-135
Orange Varying Dash - Xe-135m

Figure

7. Planning

Add the figure and some description from the Power Point talk.

8. Summary

May be a short summary